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South Asia

A Climatological Study
Volume II: Continental South Asia

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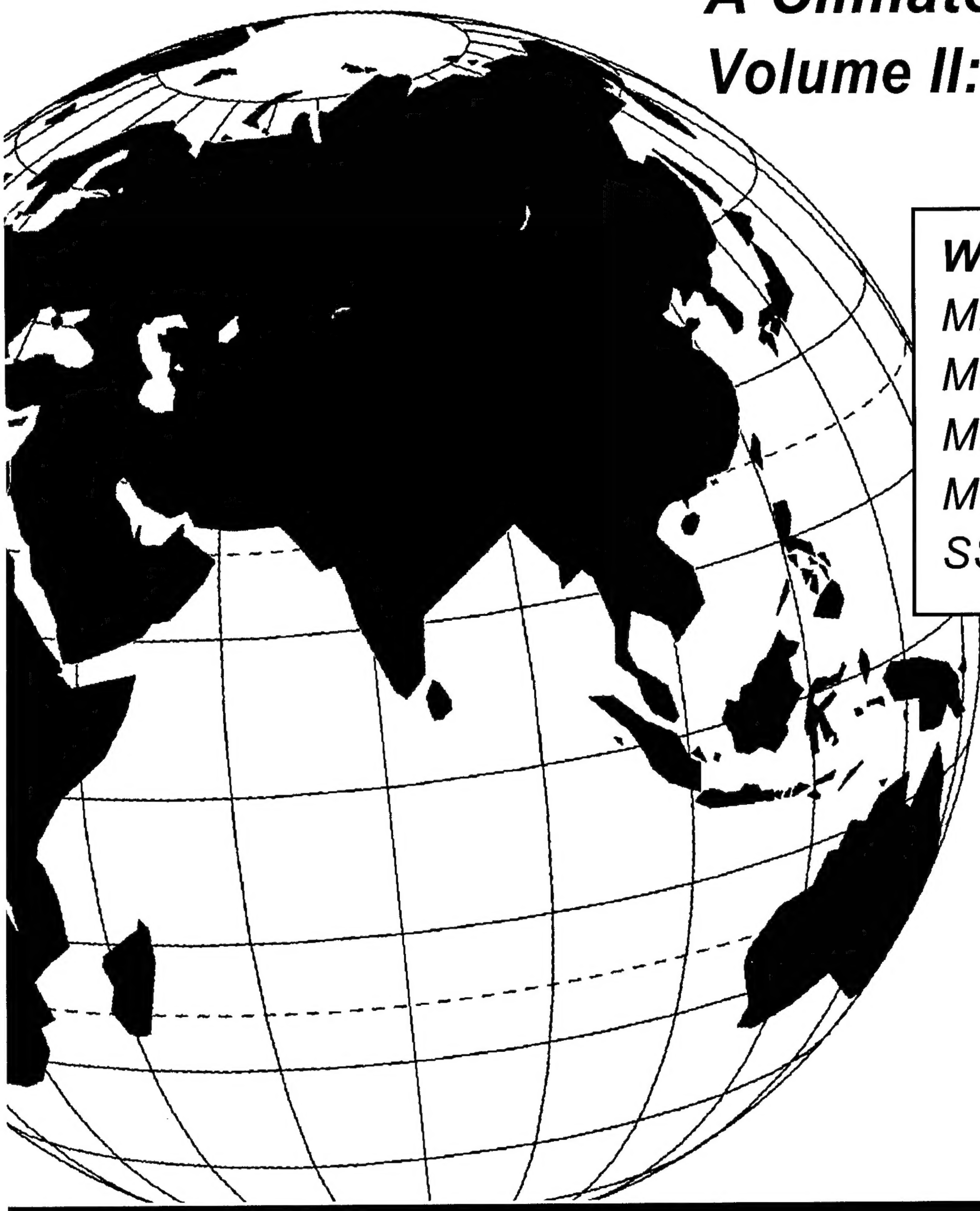

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REVIEW AND APPROVAL PAGE

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13. Abstract: This technical note is a climatological study of Continental South Asia. After describing the geography and major meteorological features of the entire region, the study discusses in detail the climatic controls of each of Continental South Asia's "five zones of climatic commonality." Each "season" is defined and discussed in considerable detail with emphasis on general weather, hazards, clouds, visibility, winds, precipitation, and temperature.

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TABLE OF CONTENTS

Chapter 5. NORTHWEST INDIA

Chapter 6. INDO-GANGETIC PLAIN

Chapter 7. HIMALAYAS

LIST OF FIGURES

LIST OF TABLES

PREFACE

This study was prepared by the Air Force Combat Climatology Center's Climate Analysis Team (now AFCCC/DOC5) in response to a support assistance request (SAR) from the Air Force Weather Agency, Offutt AFB, Nebraska.

Thanks to all the people in AFCCC's Operational Climatology Branch, who provided the immense amount of data required for the preparation of this regional climatology study. The work of Master Sergeant Joan Bergmann was especially appreciated.

Finally, the authors owe sincere gratitude to the technical editors and graphics illustrators, past and present—Mr. Gene Newman, Mr. Mike Jimenez, Technical Sergeant Gina Vorce, and Staff Sergeant Kurt Riley. Without their patience, cooperation and creativity, this project would not have been possible.

Major Joe King
Chief, Climate Analysis Team

Chapter 1

INTRODUCTION

Area of Interest. This study describes the topography, climatology, and meteorology of South Asia. The regional has been subdivided into ten zones of climatological commonality.

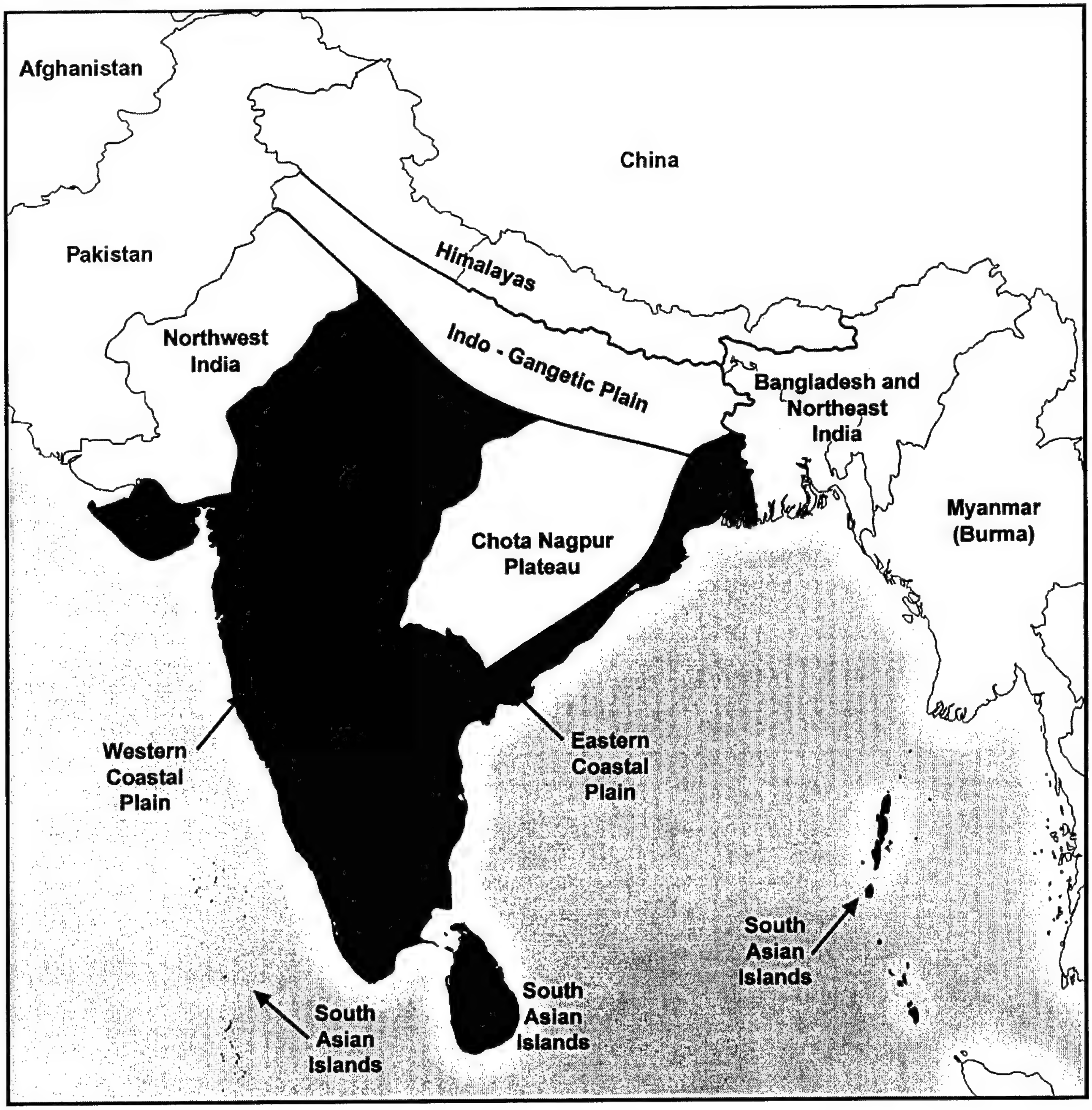


Figure 1-1. Continental South Asia (Highlighted in Yellow).

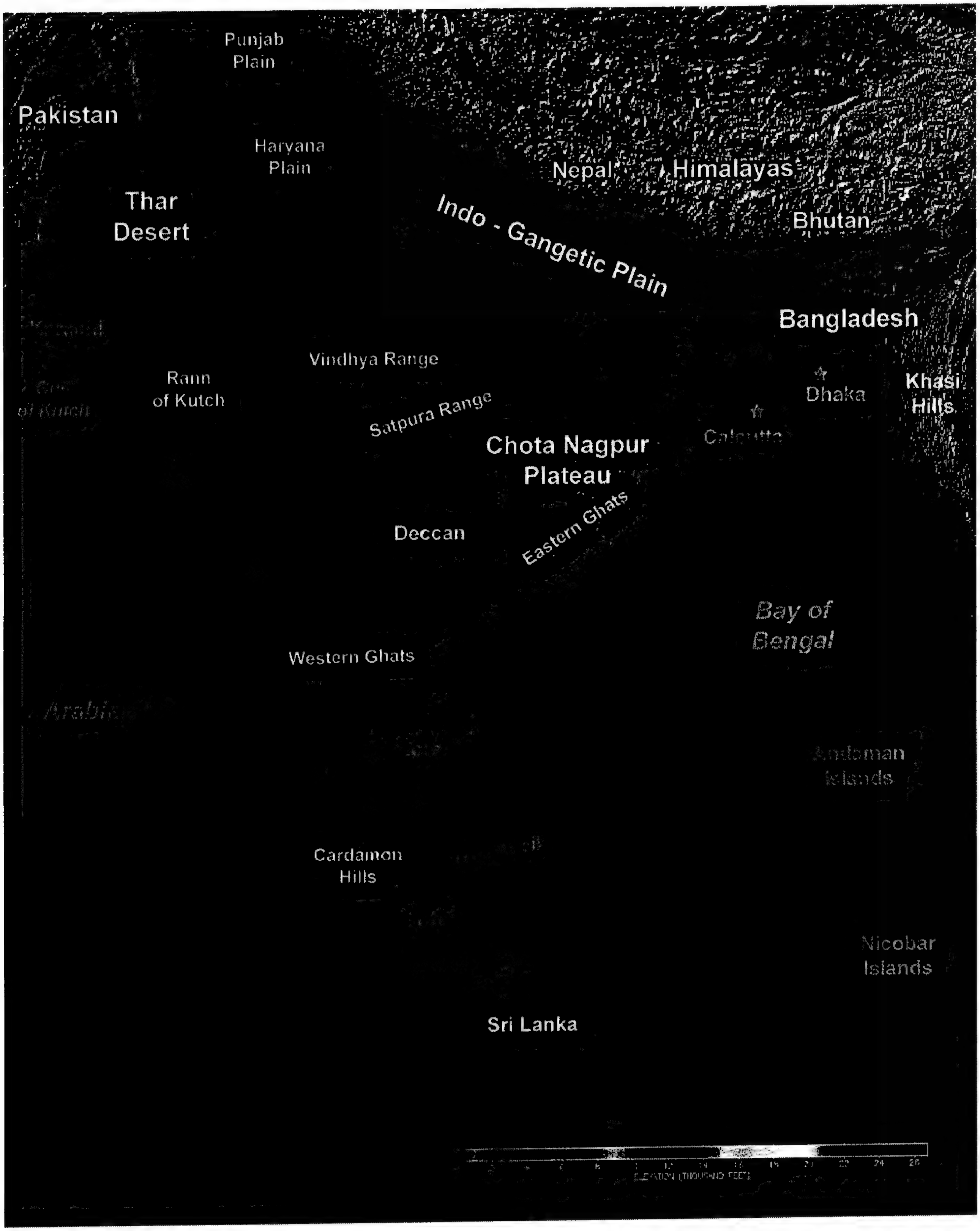


Figure 1-2. South Asia Topographical Map.

South Asia. For the purpose of this study, South Asia was divided into two volumes, Continental South Asia and Subtropical South Asia, which were further subdivided into 5 zones each. This volume, Volume II of a two-volume set, includes the following zones: Bangladesh and Northeast India, Chota Nagpur Plateau, Indo-Gangetic Plain, Northwest India, and the Himalayas. Figure 1-1 highlights the 5 zones. Figure 1-2 shows the topography of all of South Asia to aid in locating the main terrain features discussed in each zone.

Bangladesh and Northeast India. This region includes Bangladesh and East India. Bangladesh is mainly a vast river delta that handles the Brahmaputra and Ganges river systems. The Chittagong Hills in southeast Bangladesh, hills in the northeast, and highlands on the north and northwest rim of the country are included. East India is a mix of mountains and valleys. The Mizo Hills, Manipur Hills, Jaintia Hills, Naga Hills, Patkai Hills are the main feature of the eastern half of the area. The Khasi Hills and the Garo Hills of western East India (along the Bangladesh border) cover much of western East India. Along the borders of Bhutan, China, and Nepal, the Himalayas dominate. The narrow strip of land between Nepal and Bangladesh connects East India to the rest of India.

Chota Nagpur Plateau. This region includes the Chota Nagpur plateau from the southern boundary of the Indo-Gangetic plain in the north to the Godavari River in the south. The Eastern Ghats, included in the area, are the eastern edge of the region, and the western edge is marked by the Pranhita, Walinganga, Narmada, and Son Rivers. These rivers flow along the western rim of the plateau.

Northwest India. This region is bounded on the west by Pakistan, the north by the Haryana Plain, the east by the Aravalli Hills, and the south through southwest by the Vindhya Range and the north end of the Western Ghats. The area includes the Rann of Kutch, the Indian part of the Thar Desert, and the Aravalli Hills.

Indo-Gangetic Plain. The Indo-Gangetic Plain lies in northern India and southern Nepal along the base of the Himalayan mountain range between Pakistan and Bangladesh. The southern boundary lies along the northern edge of the Thar Desert in the west, the southern edges of the Yamuna and the Ganges River valleys in the center, and the northern rim of the Chota Nagpur plateau in the east.

Himalayas. The region includes Nepal and Bhutan, the Indian province of Sikkim, and the disputed territories of Jammu and Kashmir. The boundary begins at the extreme northern point of the disputed portion border between Kashmir and China. The boundary continues southeast along the Chinese-Indian border, the Chinese-Nepalese border, and the small border between China and Sikkim. Bhutan is at the eastern end of the region. The southern boundary of the region begins at the southwestern corner of Bhutan and follows the 1000-foot (330-meter) elevation contour along southern Sikkim and Nepal. The western boundary continues from the southwestern corner of Nepal, along the 1000-foot contour, through Jammu and Kashmir, to just west of the city of Dianagar, on the disputed border with Pakistan.

Study Content. Chapter 2 provides a general discussion of the major meteorological features that affect South Asia. These features include climatic controls, synoptic disturbances and mesoscale and local features. The individual treatments of each region in subsequent chapters discuss how these features uniquely affect that particular region. Meteorologists using this study should read and consider the general discussion in Chapter 2 prior to trying to understand or apply the individual climatic zone discussions in Chapters 3 through 8. This is particularly important because this study was designed with two purposes in mind: first, as a master reference for South Asia; and second, as a modular reference for each region. Chapters 3 through 8 amplify the general discussions in Chapter 2 by discussing the topography, climate, and meteorology of the zones of climatic commonality shown in Figure 1-1. These chapters provide detailed discussions in the reasonably homogenous zones of climate and meteorology. In mountainous areas, however, weather and climate are not necessarily internally homogenous. Conditions can be distinctly different in two locations which are geographically close yet topographically far apart.

In each region, topography is discussed first (including terrain, rivers and drainage systems, lakes, water bodies, and vegetation). Next, major climate controls, and, if appropriate, special climatic features are described.

Weather for each season is then discussed, organized in the following order:

- General Weather
- Hazards
- Sky Cover
- Visibility
- Winds
- Upper-Air Winds
- Precipitation
- Temperature

Conventions. The spelling of place names and geographical features are those used by the National Imagery and Mapping Agency (NIMA). Surface distances and elevations are in feet with conversions to meters or statute miles (miles) with conversions to kilometers (km). Wind speeds are in knots. Cloud and ceiling heights are reported in feet. When the term "ceiling" is used, it means 5/8 cloud coverage at and below any level unless otherwise stated. Cloud bases are above ground level (AGL) and tops above mean sea level (MSL) unless specified otherwise. Temperatures are in degrees Fahrenheit (°F) with conversions in degrees Celsius (°C). Wind speeds are in knots. Precipitation amounts are in millimeters (mm) up to 1,000 mm. From that point higher, amounts are in meters. Pressures are given in millibars (mb). Latitude and longitude are listed in degrees north, south, east or west (example: 55° N). Charts are labeled in Universal Coordinated Time (UTC or "Z" (Zulu) time) or in local time (L). Visibility is in statute miles (miles) with conversions to kilometers (km). The exceptions are times when visibility is 9,000 meters or below. Then conversions will be to meters. Thunderstorm days are those on which they have been reported. Precipitation days include those with any type of precipitation.

Data Sources. Most of the information used in preparing this study came from two sources, both within AFCCC. Studies, books, atlases, and so forth were supplied by the Air Force Weather Technical Library (AFWTL). Climatological data came directly from the Air Force Weather Climatic Database.

Related References. This study, while more than ordinarily comprehensive, is certainly not the only source of climatological information for the military meteorologist concerned with South Asia. Staff weather officers and forecasters are encouraged to contact the Air Force Weather Technical Library (AFWTL) at Asheville, North Carolina for more information.

Chapter 2

MAJOR METEOROLOGICAL FEATURES

List of Topics

Sea-Surface Conditions. Ocean currents play an important role in the region's climate. The major currents are shown in Figure 2-1 and described below. The strength and position of most of these currents fluctuate during the year, but the South Equatorial Current exists year-round.

The Indian Ocean's South Equatorial Current is strongest in August, when it forms a large, clockwise eddy with the Southwest Monsoon Current. The Southwest Monsoon Current, present from June through October, brings warm water into the northern Arabian Sea. The North Equatorial Current replaces it in December. The North Equatorial Current is strongest in January and February when a large clockwise eddy forms in the Bay of Bengal. To the south, a weak eddy flow separates it from the Equatorial Counter Current. The eastward-flowing Equatorial Counter Current is active between December and April. Its southern boundary is ill-defined as it merges into the South Equatorial Current, but the northern boundary is sharp. Figure 2-2 shows mean sea-surface temperatures (SSTs). They are above 77°F (25°C) all year except in the northern Arabian Sea and in the northern Bay of Bengal where several large rivers feed colder water into these areas during winter.

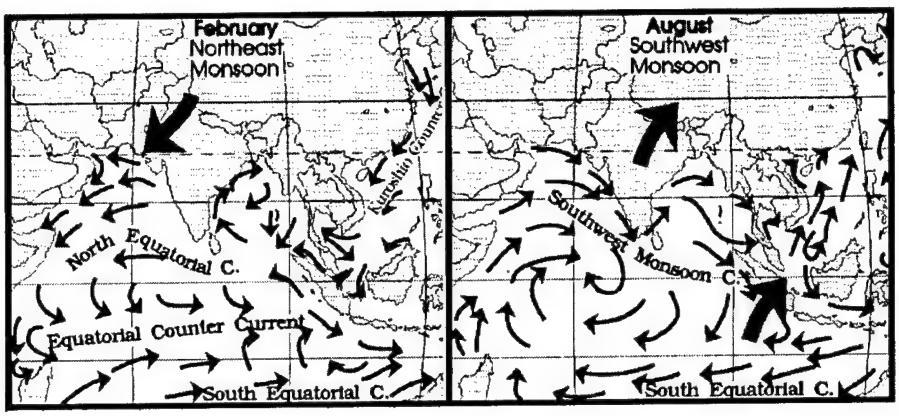


Figure 2-1. Ocean Currents during February and August. Large arrows indicate prevailing wind direction. (Traxler, et al, 1997 from Wells, 1986)

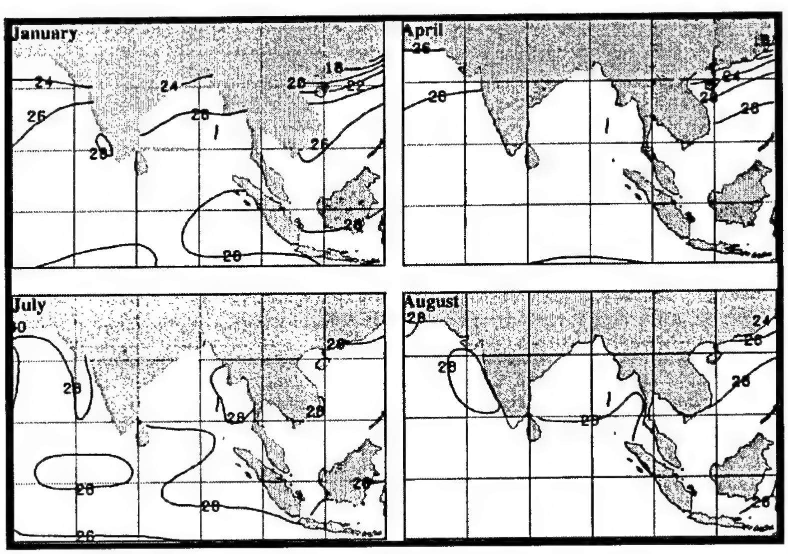


Figure 2-2. Mean Sea-Surface Temperatures. The figure shows the temperatures in degrees Celsius (°C). (Adapted from NAVAIR 50-1C-65, Vol. IX, 1965)

Major Pressure Features. These features include: the South Indian Ocean (Mascarene) high, Asiatic high, North Pacific high, Australian high, Australian low, Indian high, the Asiatic low, and the India-Myanmar trough.

South Indian Ocean (Mascarene) High. This semipermanent, Southern Hemisphere high-pressure cell provides cross-equatorial flow in April through October (see Figure 2-3). Mean core pressure ranges from 1021 mb in April to 1028 mb in August though it can exceed 1040 mb during Southern Hemisphere winter. Annual movement is mainly east-west from 30° S, 87° E in January to 29° S, 65° E in July. The high slopes equatorward and westward with height. The cross-equatorial flow from this high is a primary driver of the southwest monsoon. Its east-west shifts cause seasonal variations in the strength of the equatorial westerlies.

Asiatic High. This strong, shallow high-pressure cell, also called the Siberian high, is in place over Asia from late September to late April. It rarely extends above 850 mb. The mean central pressure is strongest (1038 mb) in January, when the high is centered over western Mongolia. The Asiatic high is created and supported by radiational cooling, though migratory arctic air masses intensify it and produce multiple centers. The core pressure may exceed 1050 mb for up to 3 days--the highest recorded pressure is 1083 mb. The Himalayas block most cold air from this high, but modified air reaches the region from the east.

North Pacific High. This subtropical high, centered west of the North American coast, is farthest north and west in July. In January, it forms a ridge near 25° N. In July, the ridge is near 35° N and extends west into the South China Sea. Its position is linked to the movement of the equatorial trough (ET).

Australian High. This thermal high exists in Southern Hemisphere winter (Northern Hemisphere summer). It is strongest in July, when it is near 28° S, 128° E, with a mean central pressure of 1022 mb. It is not as strong or persistent as the Asiatic high and is regularly traversed

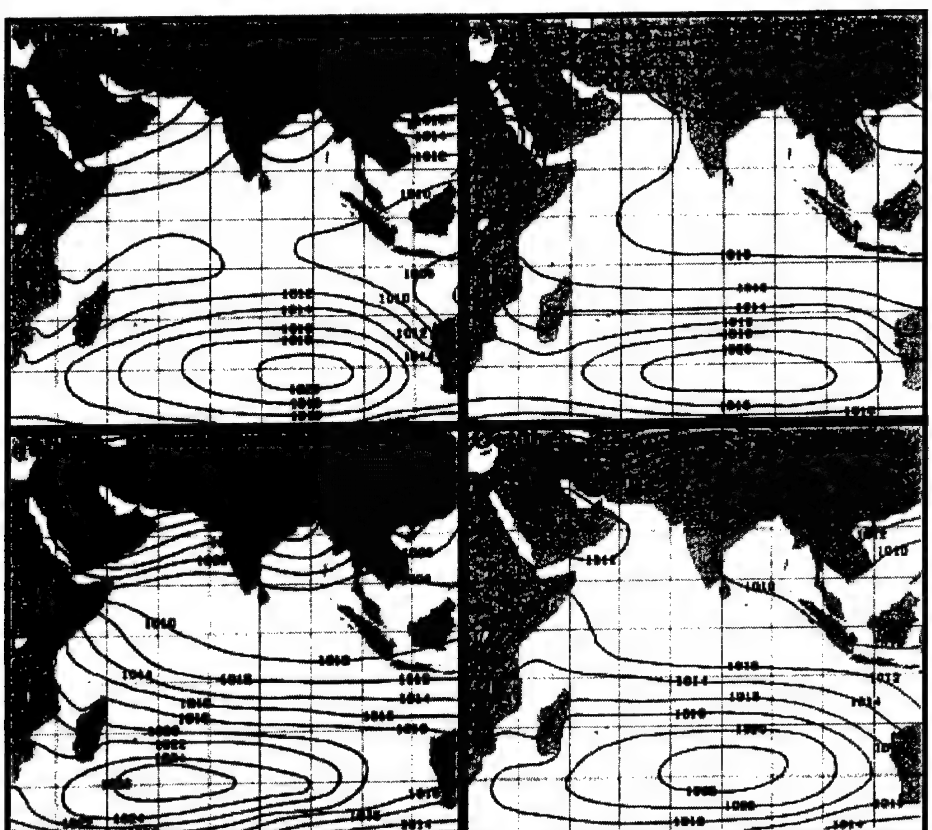


Figure 2-3. Mean Sea-Level Pressure. The figure clearly depicts the South Indian Ocean high-pressure system. (Traxler, et al, 1997 adapted from NAVAIR 50-1C-65, 1981)

by disturbances and migratory highs. It is a component of the Indian Ocean monsoon system.

Australian Low. This is a thermal low that develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

Indian High. This thermal high sets up on an irregular basis during the northeast monsoon. Because its intensity and position are highly variable, it is not evident in the mean charts shown in Figure 2-3. This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. Its impact on the weather regime varies with strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe, which use the subtropical jet to zip through the region. When the Indian high is weak it enhances western disturbances.

Asiatic Low. From May to early October, this low, also called the Thar or Pakistani heat low, anchors the eastern end of a broad, low-level thermal trough that extends from northwestern India across southern Pakistan, Iran, Saudi Arabia, and into the Sahara. The low, normally cloud-free, is strongest in July when its central pressure averages 994 mb. Its mean position in July is near 35° N 65° E (see Figure 2-3). This thermal low also draws in the ET and anchors its western end. Flow around the Himalayas dynamically enhances the troughing in India. This thermal low replaces the Asiatic high during the Northern Hemisphere summer and is, in turn, replaced by it in winter.

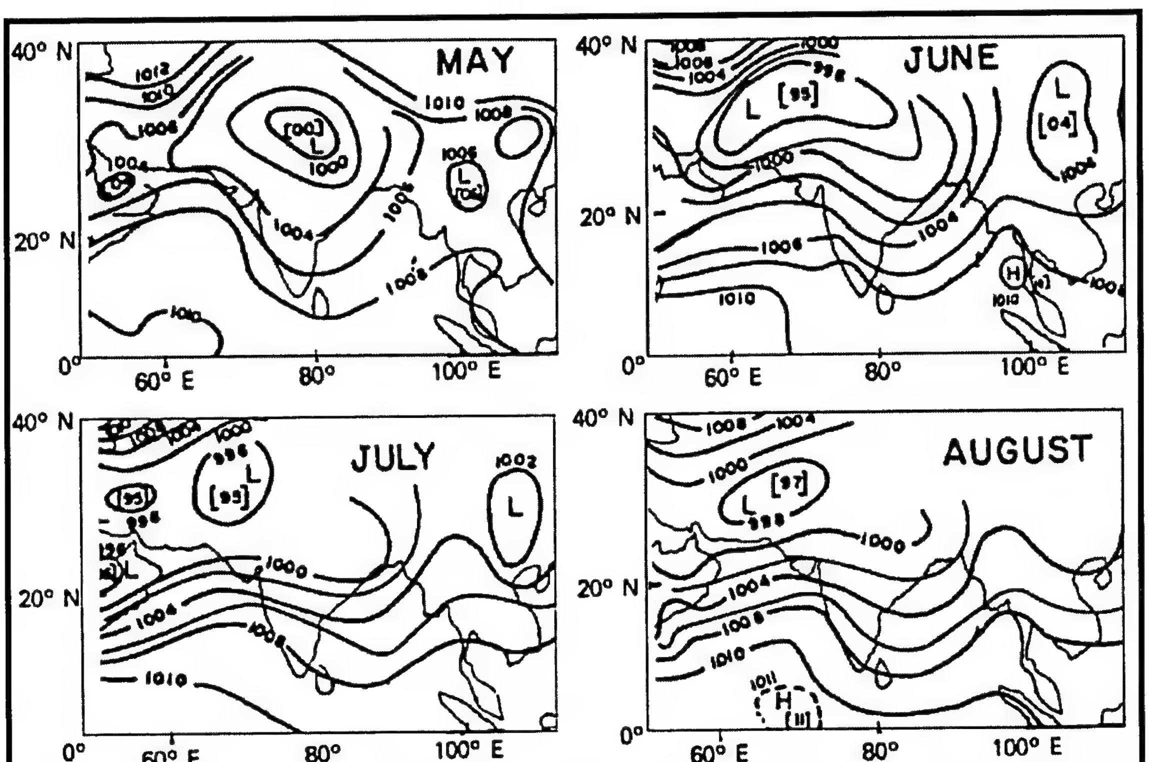


Figure 2-4. Mean Monthly Sea-Level Pressure Charts for May through August. This figure depicts development of the Indian-Myanmar Trough. (Adapted from Gadgil, 1977)

India-Myanmar Trough. This quasi-stationary trough develops in the summer along 85° E south of the Himalayas. Figure 2-4 shows the trough's mean position during the southwest monsoon. The tropical easterly jet (TEJ) over the Bay of Bengal intensifies convection along the trough, which is a preferred area for the development of monsoon depressions.

Ocean Surface Wind Flow Pattern. January's wind field shows the northeast monsoon in full swing. Northeasterly winds from the Asiatic high sweep across the northern Indian Ocean (see Figure 2-5). The flow becomes northwesterly near the equator and meets the Southern Hemisphere's trades, which become southwesterly near the equator at the equatorial trough (ET). By April, the transition to the southwest monsoon begins as the northerly flow weakens. Meanwhile, the ET begins to shift northward, but remains south of the equator. The south Indian Ocean high strengthens and shifts west by the end of April to set up the strong, south-to-north, cross-equatorial flow that drives the southwest monsoon. The convergence zone is no longer evident in the wind field. The Somali jet, which develops in this time frame, increases the wind speeds in the Arabian Sea. At the end of the southwest monsoon, as the transition towards the northeast monsoon begins, the south Indian Ocean high weakens and shifts east. The Somali jet disappears and northeasterly winds begin to flow. The ET begins to move south again.

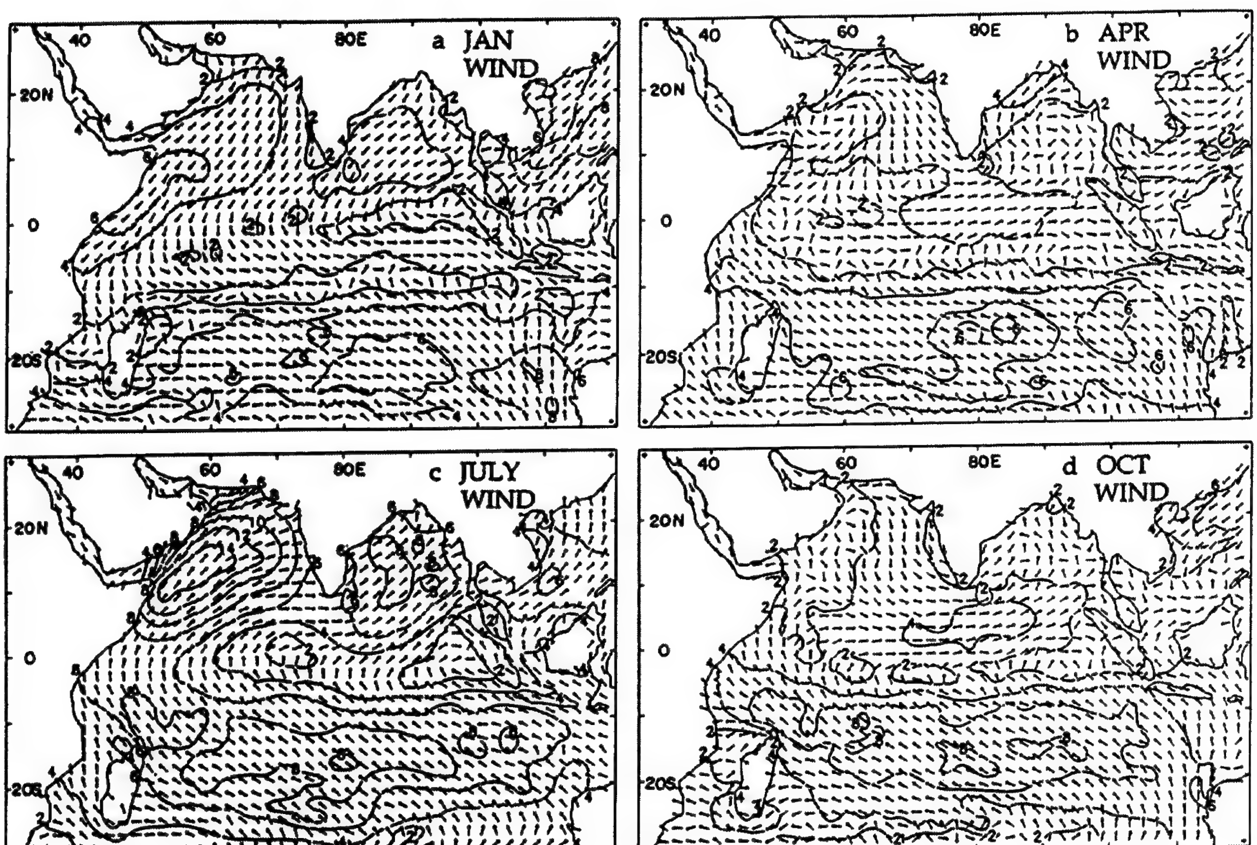


Figure 2-5. Indian Ocean Surface Wind Field . The isotachs have a 2 m/s spacing. (Hastenrath, 1991)

Mid- And Upper-Wind Flow Patterns. The Tibetan Plateau splits the mid-level flow over the northern portion of the region (see Figures 2-6a-d). The winds are weaker south of the plateau. In January, at the height of the northeast monsoon, anticyclones are prominent over the North Indian Ocean at 850 mb, and there is weak ridging at 700 mb. In the upper-levels, strong westerly winds are present over and just to the south of the plateau. The winds decrease as one moves further south over the region.

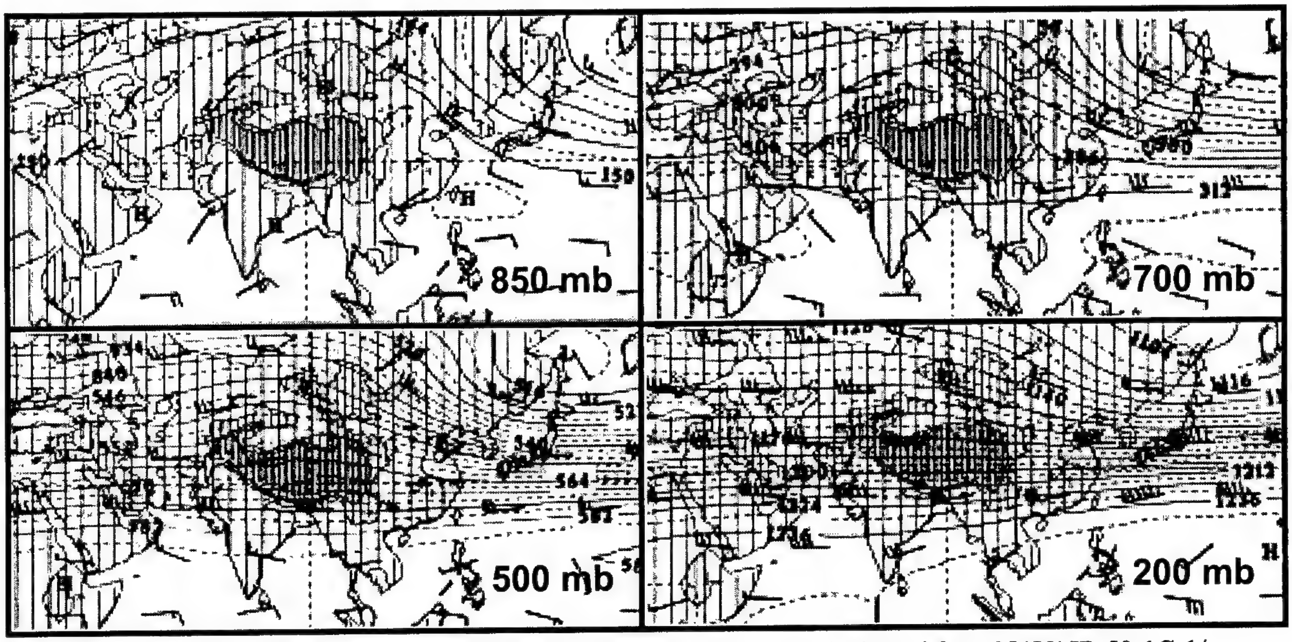


Figure 2-6a. Mean Mid- and Upper-Airflow Patterns—January. (Adapted from NAVAIR 50-1C-1/ AWSTR-89/001, Vol. 1, 1989)

As the transition to the southwest monsoon begins, the April flow patterns are weak at all levels. This is particularly true in the lower levels as the ET migrates north.

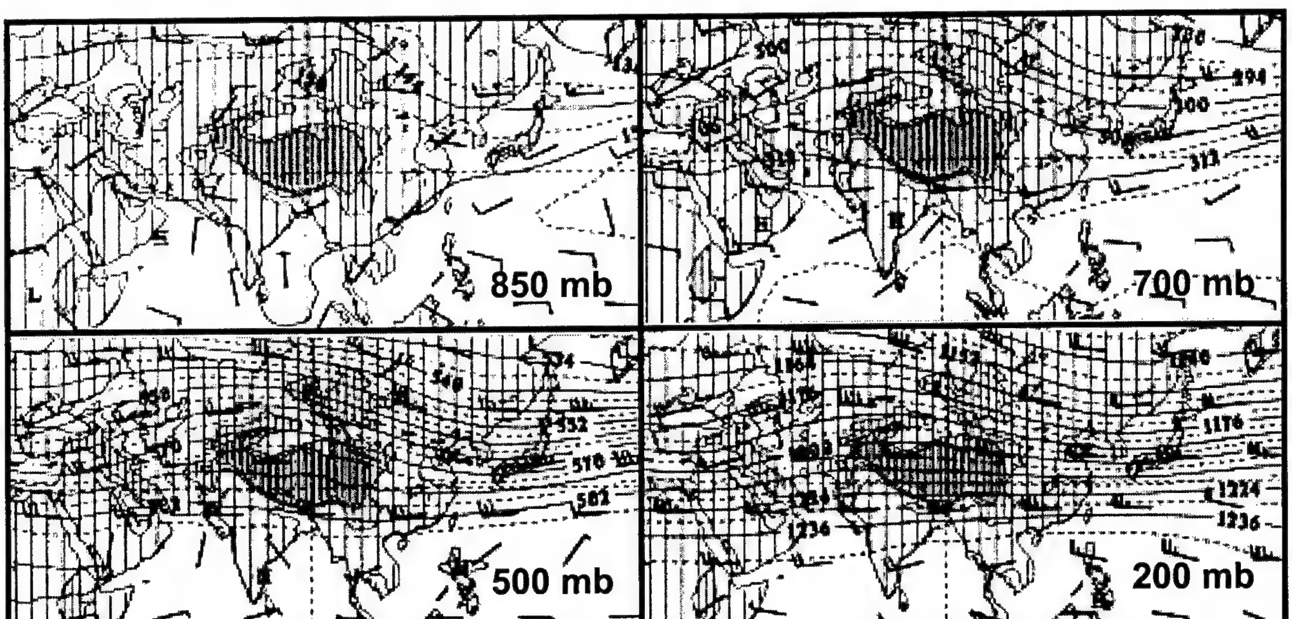


Figure 2-6b. Mean Mid- and Upper-Airflow Patterns—April. (Adapted from NAVAIR 50-1C-4/ AWSTR-89/004, Vol. 4, 1989)

Semipermanent Climate Controls

July's 500-mb pattern is complex because 500 mb is the transition level between the low-level southwest monsoon and the 200-mb tropical easterly jet (TEJ). The presence of a low over India indicates weak, indeterminate flow. Meanwhile, the upper-level Tibetan anticyclone establishes itself over the region.

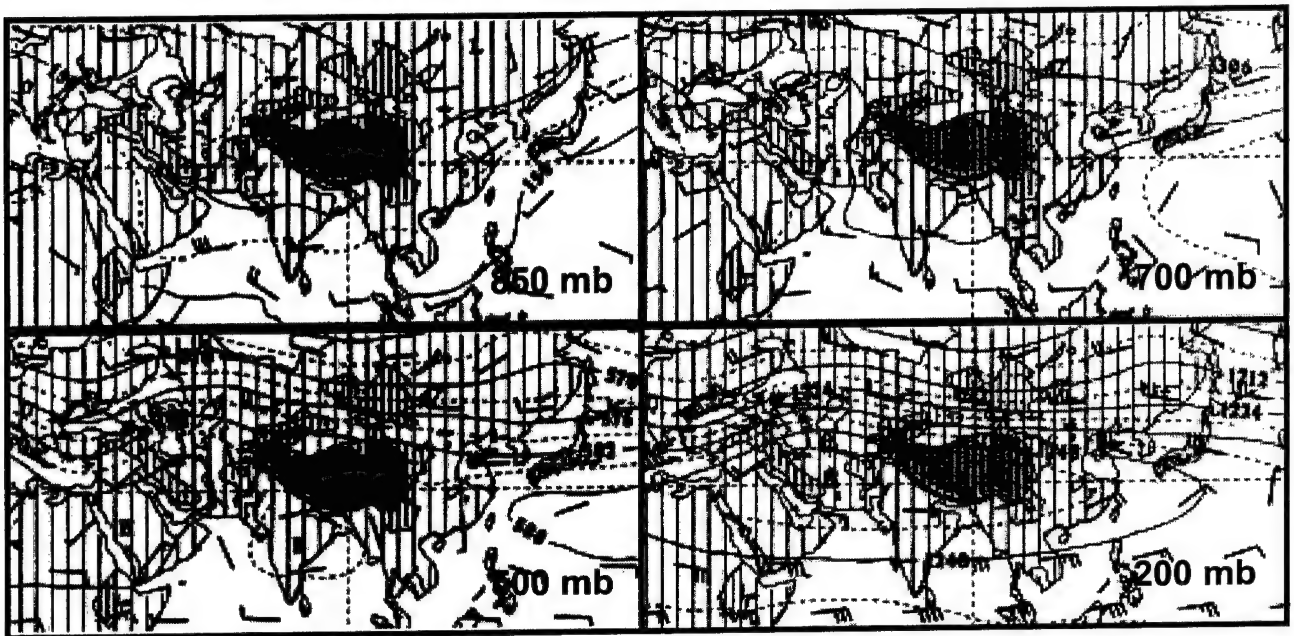


Figure 2-6c. Mean Mid- and Upper-Airflow Patterns—July. (Adapted from NAVAIR 50-1C-7/ AWSTR-89/007, Vol. 7, 1989)

By October, the transition to the northeast monsoon is well underway. The flow patterns are weak once again as the ET migrates south. An 850-mb thermal low forms over the Bay of Bengal though it disappears by November. In the upper-levels, the Tibetan high and the TEJ disappear, and the westerly winds migrate south.

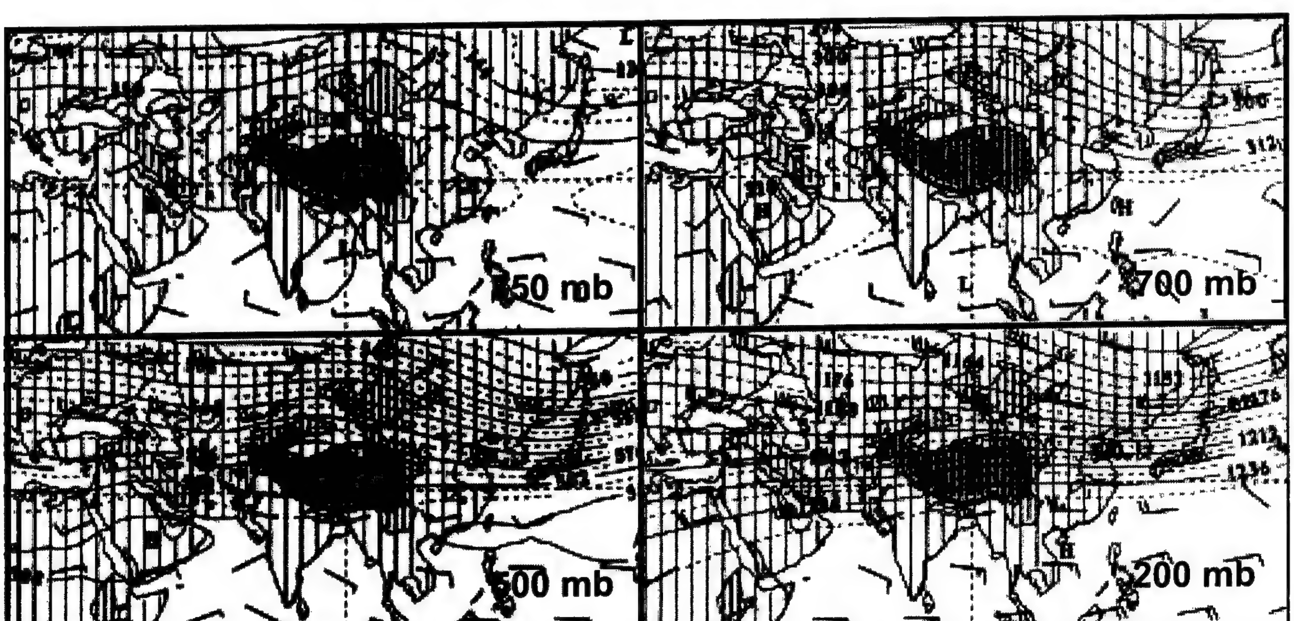


Figure 2-6d. Mean Mid- and Upper-Airflow Patterns—October. (Adapted from NAVAIR 50-1C-10/ AWSTR-89/010, Vol. 10, 1989)

Subtropical Ridge. This upper-level feature (see Figures 2-6a-d) has a mean annual position near 15° N, centered at about 130° E. The western perimeter of the ridge extends into the Indian Ocean. The ridge moves north and south with the sun and reaches its southernmost position in January. It provides outflow for convection from the equatorial trough and tropical cyclones. During the southwest monsoon, the Tibetan anticyclone dominates the subtropical ridge over the Indian Ocean.

Tibetan Anticyclone. This upper-level feature develops in April when a high-pressure cell over southeast Asia migrates northwestward to the Tibetan Plateau. Figure 2-7 shows its mean position in May and July. At the plateau's surface (about 600 mb), a heat low forms and is surrounded by a ring of highs along the plateau's mountainous rim. The thermal low is sustained and deepened by the intense heating of the plateau. As it strengthens, so does the anticyclone above it. The anticyclone also interacts with the subtropical ridge aloft. This interaction causes the Tibetan anticyclone's position to vary; if it shifts eastward of 90° E, severe drought results over much of the subcontinent.

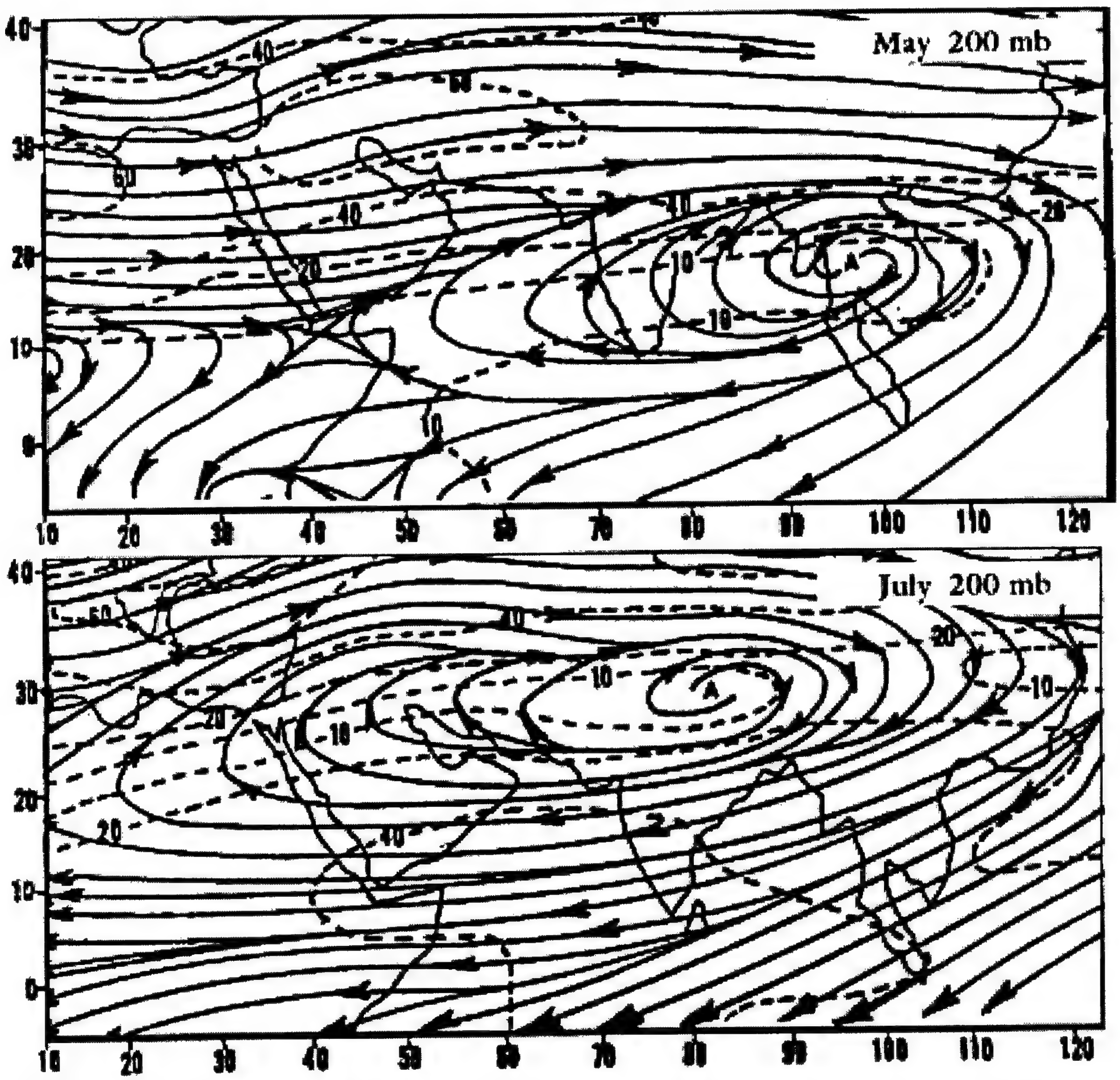


Figure 2-7. Mean May and July Positions of the Tibetan Anticyclone. The figure shows the migration of the Tibetan Anticyclone as it strengthens. (Higdon, et al, 1997 from Chenglan, 1987)

The Tibetan anticyclone intensifies the easterlies to the south and provides the upper-level divergence important for southwest monsoon rains. Its northeastward movement helps establish the southwest monsoon. Figure 2-8 shows an example of this process. The numbers represent 5-day periods that began 16 April and ended 4 July 1979. The abrupt northward jump between Periods 5 and 6 (11-15 May) coincides with the onset of the southwest monsoon. The Tibetan anticyclone is established over the Tibetan Plateau during period 14 (20-25 June). After period 14, the anticyclone splits. One portion goes west and the other goes east. By period 16, the anticyclone has clearly broken into two cells, one in central China and the other well to the west. The number 15 (not shown in Figure 2-8) is the western cell, while number 16 is the China cell.

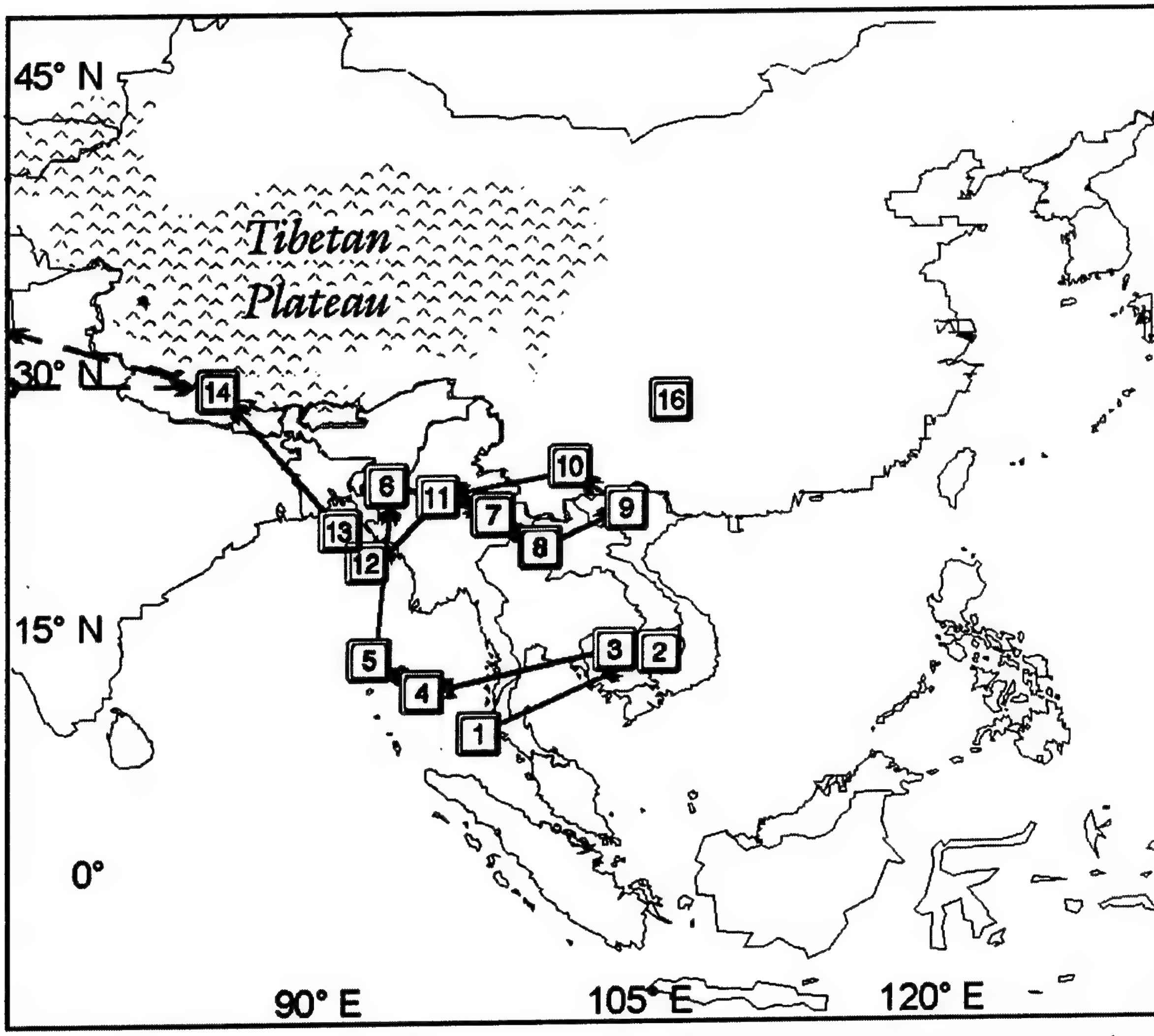


Figure 2-8. Mean Positions of the Tibetan Anticyclone at 200 mb. See text for meaning of the numbers. (Traxler, et al, 1997 from He, et al, 1987)

Jet Streams. Three primary jet types affect this region: the subtropical jet (STJ), the tropical easterly jet (TEJ), and tropical low-level jets.

Subtropical Jet (STJ). This is the southerly branch of the mid-latitude westerlies. (The northerly branch, the polar jet, rarely affects South Asia directly.) During the southwest monsoon, the STJ is relatively weak and lies north of the Tibetan Plateau. As the seasons transition into the northeast monsoon, the STJ intensifies and moves south of the plateau. Figure 2-9 shows the STJ's mean position during January, April, July, and October. The mean height of the STJ is near 39,000 feet; its mean speed is 75 knots in January and 50 knots in July. The STJ provides upper-level steering, shear, and outflow. Rainfall is often concentrated along the jet axis. Although the STJ shows less variability in its daily position, its seasonal variability is great. By the end of May, the westerlies retreat north of the Tibetan Plateau—a prerequisite for the start of the southwest monsoon. Deformation of the wind flow around the mountains creates a distinct pattern during the southwest monsoon with a trough that shifts from the Bay of Bengal to the Arabian Sea.

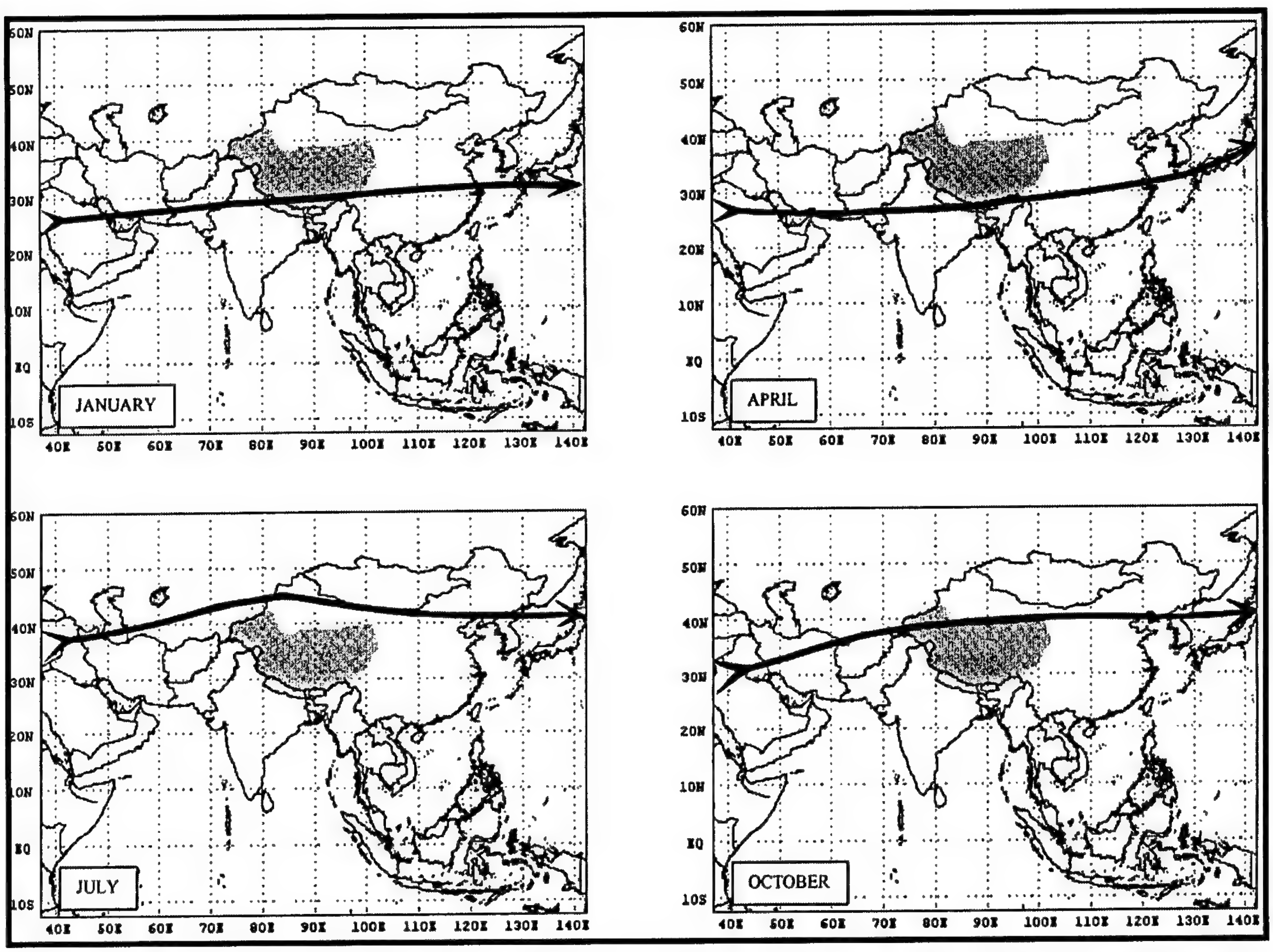


Figure 2-9. Mean Subtropical Jet Stream Positions. The figure shows the mean postion of the subtropical jetstream during each of the seasons. (Traxler, et al, 1997 adapted from Marcal, 1968)

Tropical Easterly Jet (TEJ). This Northern Hemisphere summer jet in the upper-level easterlies develops at or above 200 mb as outflow from the southern edges of the Tibetan anticyclone. Its entrance region lies from over the South China Sea to the western Pacific as far east as Guam (about 140° E). This jet is strengthened over South Asia by the strong temperature contrast between the warm land mass and the relatively cool equatorial water. The TEJ is limited to the southwest monsoon and exists from late June into early September. The mean axis position is near 15° N, 4-5 degrees south of the surface equatorial trough, but it oscillates between 5° and 20° N (see Figure 2-10). The strongest winds are between 73° and 80° E where

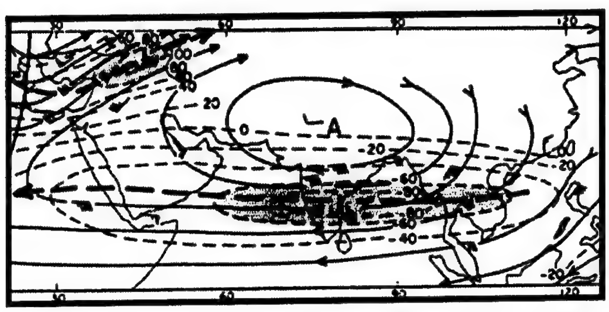


Figure 2-10. Analysis of Tropical Easterly Jet at the 200-mb Level on 25 July 1955. Streamlines are represented by the solid lines, while isotachs (knots) are depicted by dashed lines. JW = westerly jet maximum, JE=easterly jet maximum, A=anticyclone, C=cyclones. Heavy dashed lines with arrows indicate positions of jet axis. (McGregor and Nieuwolt, 1997 adapted from Koteswaran, 1958)

maximum speeds reach 90 knots; the mean wind speed is 60 knots. The jet follows the highest sea-surface temperatures. Since a cool area often develops in the South China Sea north of Borneo, the TEJ sometimes splits into two axes near 5° and 20° N (see Figure 2-11). The northern branch is stronger. The TEJ's position and intensity significantly affect the southwest monsoon rains and low-level trade winds. Fluctuations in the TEJ's strength are connected to "pulses" in the monsoon flow. The TEJ also provides an outflow mechanism for ET convection and for convection with the India-Myanmar trough. It causes upper-level divergence in the northern Bay of Bengal directly over the convergence provided by the ET. This triggers monsoon depression development.

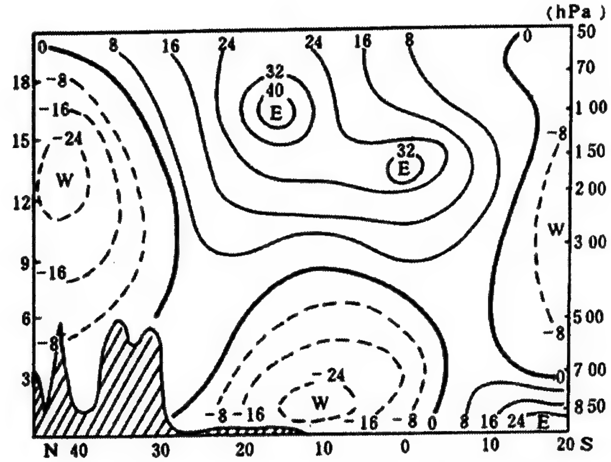


Figure 2-11. Cross-Section of the Mean Zonal Component along 80° E for July. Solid (dashed) lines denotes isotach of easterly wind (westerly wind) in m/s. (Higdon, et al, 1997 from Yihui, 1994)

Tropical Low-Level Jets. Two north-flowing, low-level jets form over the Indian Ocean between February and October. Figure 2-12 shows their locations. The entrance regions for both jets are over warm seas. One jet develops in the Bay of Bengal near the equator near 90° E. It flows northeastward over the northwest Myanmar coast. The second, the Somali jet (also known as the East African jet), is the stronger of the two.

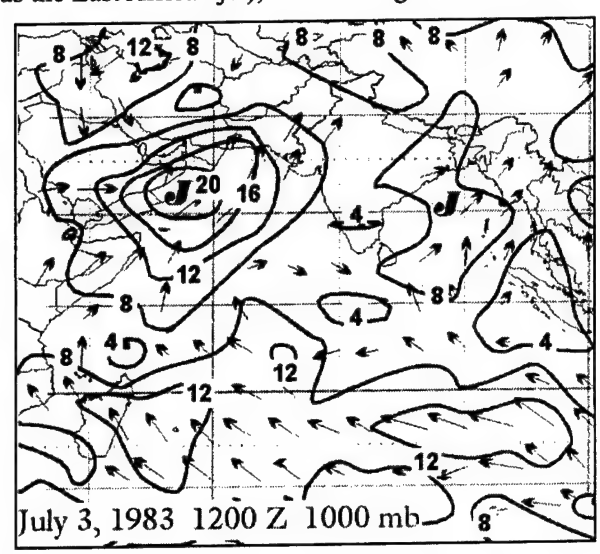


Figure 2-12. Mean Positions of Low-Level Jets. The Isotachs (knots) and arrows show mean flow. The large "Js" show jet core positions. (Traxler, et al, 1997 adapted from Zhou, et al, 1990)

It is active from February to late October (see Figure 2-13), when flow from the South Indian Ocean high is compressed into a high-speed jet core along the eastern edge of Africa. The core normally passes just north of Madagascar heading to the northwest and turns to the northeast across Somalia. The mean core is usually at 2,000 feet MSL over the Indian Ocean.

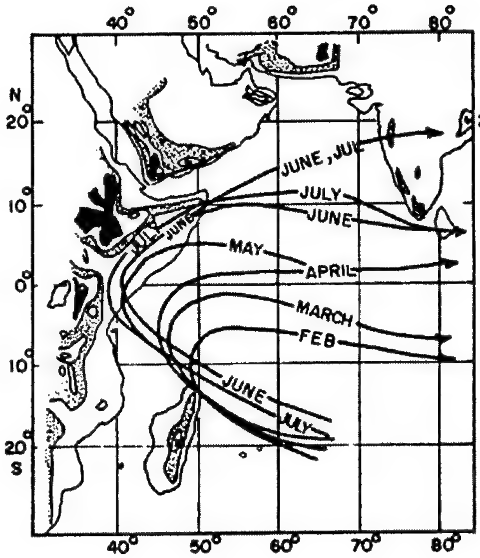


Figure 2-13. Monthly Progression of the Axis of the Somali Jet. (Hastenrath, 1988 adapted from Findlater, 1971)

Figure 2-14 shows the mean July monthly airflow at 3,000 feet MSL across the western Indian Ocean basin.

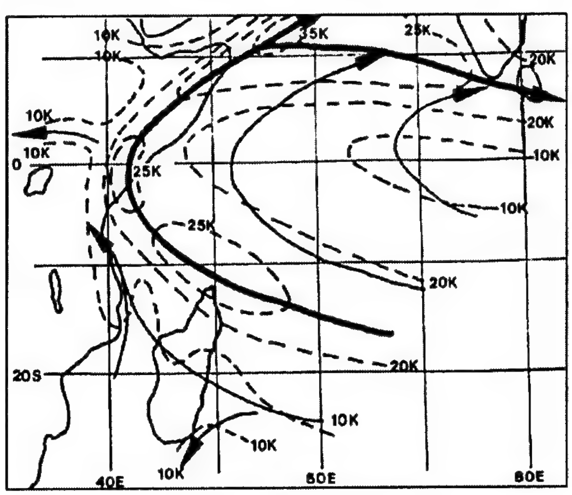


Figure 2-14. July Mean Monthly Airflow at 3,000 Feet (900 Meters). Solid lines are streamlines; dashed lines are isotachs in knots. (Vojtesak, et al, 1992 adapted from Findlater, 1971)

The Somali jet has mean core speeds of 25-40 knots. This jet first appears in February. It normally strengthens from April to July, then weakens from August to October. Highest speeds are near the equator across Kenya and Somalia, where speeds of 100 knots have been reported. These extreme speeds may be related to Southern Hemisphere cold surges. Like most low-level jets, the Somali jet shows a marked diurnal variation. Peak core speeds occur near dawn, and minimum core speeds occur in late afternoon. Surface speeds beneath the core are the opposite. The minimum speeds occur at dawn, maximum speeds occur in mid-afternoon. The Somali jet is one component of the southwest monsoon as it drives the equatorial westerlies. Fluctuations in its strength appear to be linked to surges in the monsoon flow.

Monsoon Climate. During Northern Hemisphere winter, the warm oceanic ridge and the Asiatic high combine to form a continuous belt of high pressure. In summer, heat lows replace the Asiatic high. This seasonal reversal of the pressure gradient gives rise to the northeast and southwest monsoons that affect South Asia (see Figure 2-15). The term "monsoon," from the Arabic "mawsim" or "season," is commonly applied to those areas of the world where there is a seasonal reversal of prevailing winds. The accepted definition of a monsoon climate is based on the following criteria:

- Prevailing wind direction shifts by at least 120° between January and July.
- The average frequency of prevailing wind directions in January and July exceeds 40 percent.
- The mean resultant wind in at least one of the months exceeds 6 knots.
- Fewer than one cyclone-anticyclone alternation occurs every 2 years in either month in a 250 x 250 NM (500 x 500 km) square.

Equatorial Trough (ET). Also called the monsoon trough, intertropical convergence zone (ITCZ) or near-equatorial trough (NET) for the South Asia region by various authors, the ET marks a zone of wind discontinuity with horizontal velocity convergence and upward vertical motion. There is cloudiness along and near this zone, aligned in nearly an east-west direction.

The ET oscillates north-south with the sun. In the Indian Ocean, the ET separates the westerlies in the near-equatorial region and the easterly trade winds on the other side of it. The westerlies result from the southeast trades (source south Indian Ocean high) that deflect eastward after crossing the equator.

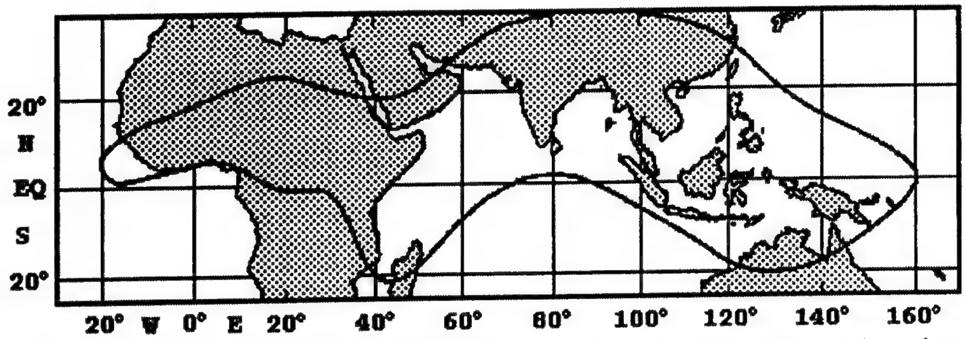


Figure 2-15. Monsoon Region. Area satisfying Ramage's monsoon criteria is enclosed by the solid line. (Adapted from Ramage, 1995)

Source regions for the easterly trades are the North Pacific high and the Australian high during the summer, and the Asiatic high in the winter. See Figure 2-16 for the positions of the ET in January and July.

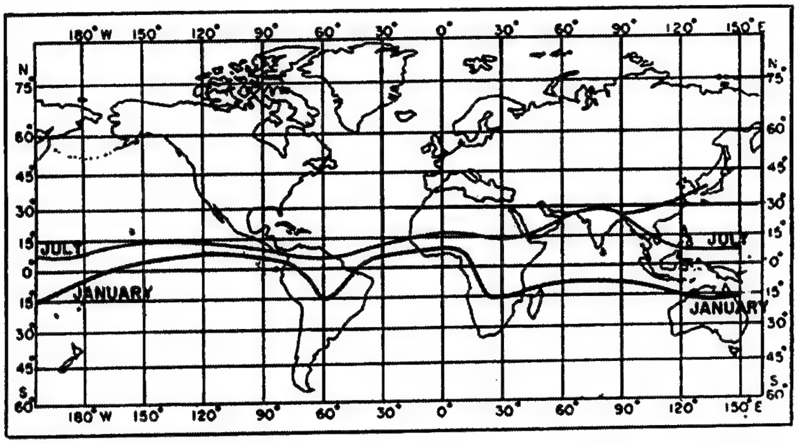


Figure 2-16. Surface Positions of the Equatorial Trough (ET) in January and July. (Asnani, 1993)

Movement. The ET's annual movement lags behind the sun by nearly two months (Figure 2-17). The highest temperatures occur about a month after solstice over the large continental areas, and nearly two months later over the oceans and in the upper air. During its annual oscillation, the ET migrates farthest from the equator into the summer continental regions.

Structure. Tropical maritime air is found on the equatorial side of the ET. The air on the poleward side comes from the higher latitudes. It undergoes much subsidence and is still relatively warm, dry and stable. It is also warmer than the tropical maritime air on the equatorial side. Because the ET in the Indian Ocean and surrounding lands is a region of low pressure, it slopes upward towards cooler air. Thus, the vertical slope of the ET is generally towards the equator. The slopes are not uniform with height; they fluctuate with small changes in density and wind speed. Figure 2-18 shows the approximate positions of the ET's various levels for January and July. The equatorial trough is deepest over India during the southwest monsoon, where it can be located up to the 400-mb level on upper-air charts. Elsewhere, it is generally located only up to the 700-mb level.

Associated Weather. The height and slope of the ET are the main factors in the distribution of weather around it. The slope is highly variable in space and time; its height ranges from 6,500 to 33,000 feet. Relative cool, moist air is on the equatorial side with relatively dry, warm, and stable air on the poleward side. Broad bands of

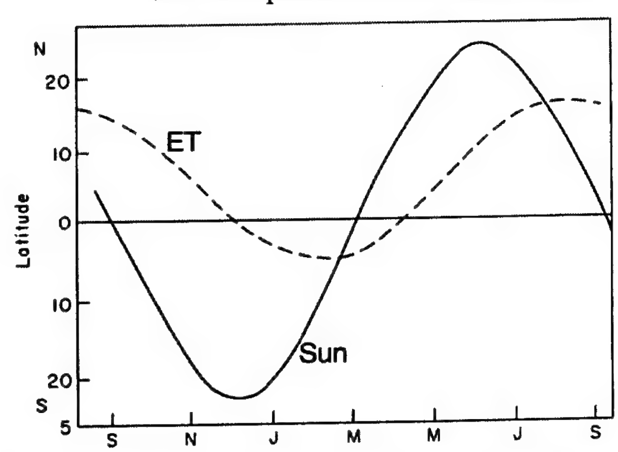


Figure 2-17. Annual Movement of Sun's Zenith Position Versus the ET. (Riehl, 1979)

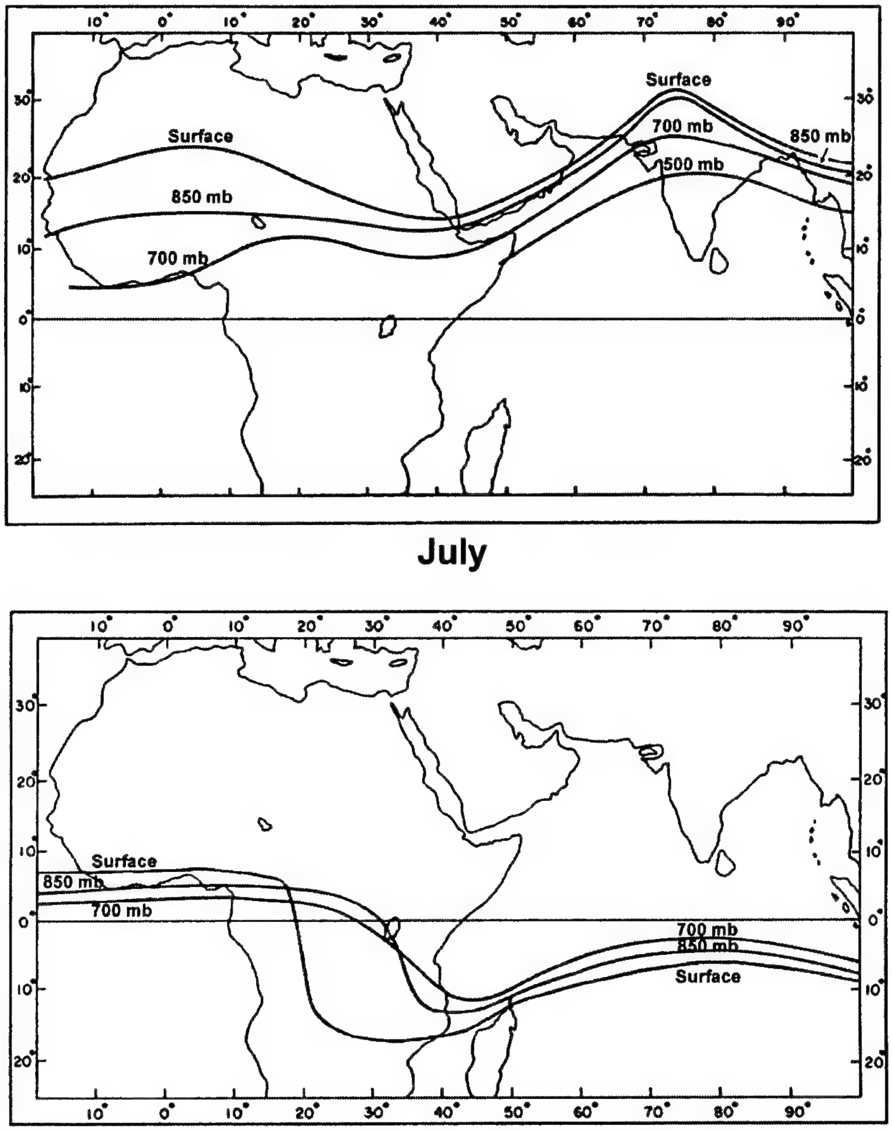


Figure 2-18. Equatorial Trough (ET) Slope for January and July. Depicts the climatological mean surface, 850 mb and 700 mb positions of the ET. (Asnani, 1993)

relatively dry, easterly winds flow above the ET discontinuity out of the subtropical anticyclones. Clouds form in the moist layer on the equatorial side. Large cumuliform formations are possible if the moist layer is more than 10,000 feet deep. Vigorous thunderstorm activity and heavy precipitation occur within these formations. The rest of the area may get shallow cumulus or stratocumulus. This results in the maximum cloudiness being found 125-300 miles (200-500 km) on the equatorial side of the ET's surface position.

When associating weather with the ET, the following points apply:

- If the underlying moist layer is shallow, as over a desert region, there may be no rainfall.

- The ET is not a long, unbroken band of heavy cloudiness. It consists of cloud-clusters separated by large cloud-free regions. Each cloud cluster has mesoscale circulations that create lines of clouds separated by cloud-free zones. This is due to the

movement of synoptic-scale tropical waves in the vicinity of the ET.

- The ET is not a static zone with steady-state conditions of cloudiness. There are oscillations in the position and intensity of vertical movement in the region. There are also oscillations, influenced by land-sea breezes, with a period of one day. Migratory tropical and extra-tropical waves can cause oscillations with periods up to 4-5 days. Oscillations with larger periods are associated with the position and intensity of planetary-scale features like the Hadley cell.

Northeast Monsoon. The Asiatic high dominates the Asian continent during the Northern Hemisphere winter months. As a result, the pressure over Asia decreases rapidly southward towards the ET, which is south of the equator. South of the Himalayas, the pressure gradient is weak and results in a northerly wind flow across the Indian subcontinent. The Himalayas prevent the direct movement of arctic air into South Asia. Instead, modified air moves into the Indian subcontinent indirectly. One route is from the northwest across the mountains of Pakistan. It is also channeled into the region from the east around the southern periphery of the plateau. The region also receives air from the southern slopes of the Himalayas. It is possible the winter circulation is fed, in part, by subsiding air over the northern part of the subcontinent. In any case, the resulting circulation is a fairly weak, dry northerly air flow. Little rainfall occurs over most of the region and the skies are generally clear.

Southwest Monsoon. This season is at full strength between June and September. Rainfall over northwestern India begins in late May or early June and ends in early to mid-September. Most locations receive 75-90 percent of their annual rainfall during it. The southwest monsoon develops in response to the northward movement of the western Pacific Ocean's subtropical high-pressure ridge. The process begins in April. As the subtropical ridge moves northward and strengthens, changes in the general circulation pattern take place. The Asiatic low replaces the Asiatic high. The subtropical westerly jet moves north of the Tibetan Plateau and gradually decreases in intensity. The Tibetan anticyclone moves over the plateau. The TEJ sets up south of the Himalayas. In the meantime, the equatorial trough begins its northward movement into the north Indian Ocean while the Somali jet establishes itself in the western Indian Ocean. All of this activity results in cross-equatorial flow that allows the air stream from the south Indian Ocean high to reach the Himalayas. These southerly winds reach peak intensity and farthest north in July and August then retreat southward in September (see Figure 2-19).

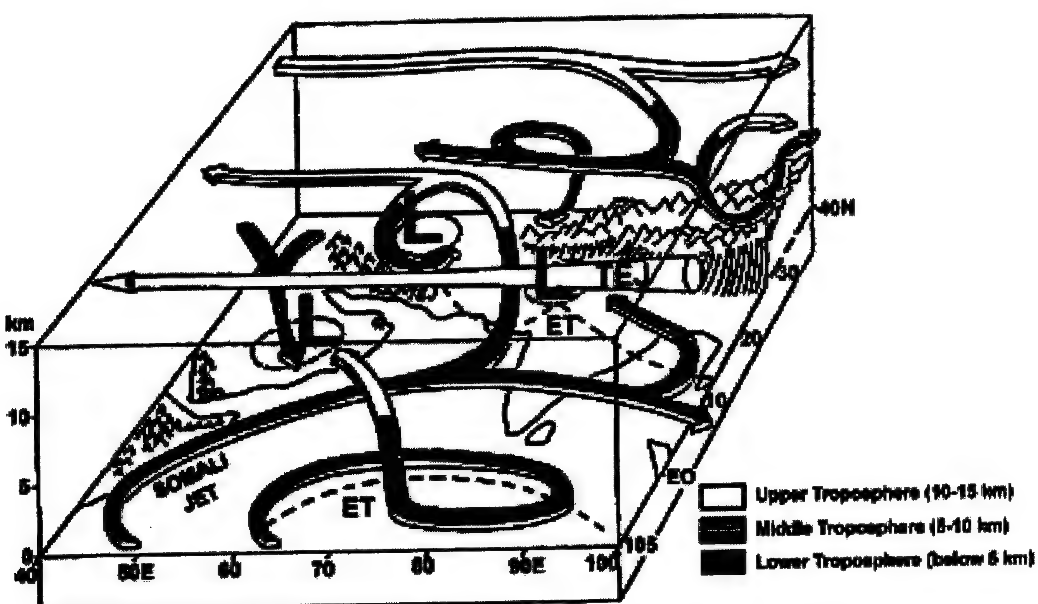


Figure 2-19. Southwest Monsoon Circulation over the Indian Ocean. (Schematic adapted for use by Air Weather Service, 1998. Original source unknown.)

The monsoonal wind flow brings west to southwest flow of maritime tropical air to the Indian subcontinent. The transport of air into the northern hemisphere occurs across a line from a point near eastern Africa to a point just west of Sumatra. This airmass often attains considerable depth, from the earth's surface to 20,000 feet. This air is quite humid; its relative humidity rarely falls below 70 percent. During July and August, the relative humidity is generally more than 80 percent throughout the airmass. Consequently, the temperature lapse rate is always near the moist adiabatic, which leads to intense thunderstorm activity. Afternoon thunderstorms over land areas are the rule.

Controlling Mechanisms. Several features maintain, control, and regulate monsoon circulation. Differential heating, coriolis force, and condensation or evaporation of water vapor trigger the monsoon.

• Differential heating. This arises from the differing responses of ocean and land to solar radiation. Since water has a higher heat capacity than dry soil, its specific heat is larger and it can distribute heat through a greater depth by mixing. As a result, the annual cycle of the water's surface temperature has a smaller amplitude than land temperature. It also lags behind solar heating by about two months. Air in contact with the surface can gain solar energy absorbed by that surface and convect heat upward. As a result, differential heating leads to a large reduction of atmospheric pressure over land. This is especially true over the Indian subcontinent in Northern Hemisphere spring. The pressure difference created is minimized by a nearly horizontal flow of cooler, denser air from the ocean. As cooler air sinks, it forces warmer air over the land upward. This initiates a circulation in a vertical plane, whose lower arm constitutes the familiar monsoon winds.

• Coriolis deflection. The earth's rotation strongly influences monsoonal circulation. It deflects the winds towards the right in the Northern Hemisphere and towards the left in the Southern Hemisphere. Magnitude of deflection is a function of latitude.

• Condensation or evaporation of water vapor. Evaporation/condensation is another mechanism of the southwest monsoon. The Indian Ocean water forms a vast reservoir of stored solar energy. Some of the energy is lost to evaporation. The energy enters the atmosphere when water vapor condenses. In a monsoon environment, this occurs in air that moves toward or over land as it ascends. The heat adds additional buoyancy to that provided by the underlying surface. This favors further ascent and provides a stronger inflow of moist air at the lower levels from ocean to land. Since air holds more water vapor at higher temperatures, this moisture transport tends to be greatest in late summer when the sea surface and air temperatures are at their highest. Thus, the southwest monsoon circulation is strongest in the late summer. Uninhibited development of the monsoon circulation is prevented by the clouds that develop in ascending air. The clouds limit the solar radiation received at the surface.

Development. The development of the southwest monsoon usually begins first over southern China then progresses westward over Southeast Asia. It does not begin over South Asia until more than a month later. The reason for this delay is the upper-air circulation at 20,000-26,000 feet. Westerly winds prevail at this level over the entire area south of the Tibetan plateau during the Northern Hemisphere winter. These conditions are similar to those at the 700-mb level (see Figure 2-20). This circulation pattern induces an upper-level trough over the Bay of Bengal. By late Northern Hemisphere spring, this trough aids in the development of upper-level easterlies over southern China and Southeast Asia. The easterlies eventually evolve into the TEJ, which is necessary for the development of the southwest monsoon. They constitute the upper return movement

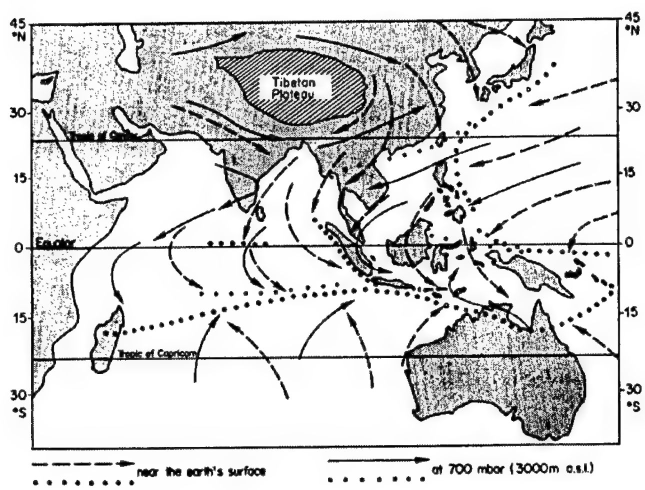


Figure 2-20. Circulation Pattern of the Asian Northeast Monsoon. December to March wind flow patterns are depicted by the arrows while dots represent convergence zones. (McGregor and Nieuwolt, 1998)

of air towards the equator, which makes them a part of the southwest monsoon circulation (see Figure 2-21). the southwest monsoon varies from as early as 11 May to as late as 18 June. The average date is 2 June with a standard deviation of 8 days. The start of the southwest monsoon over South Asia implies the ET has arrived over the region. It further implies the ET is moving north and will not recede south until its withdrawal.

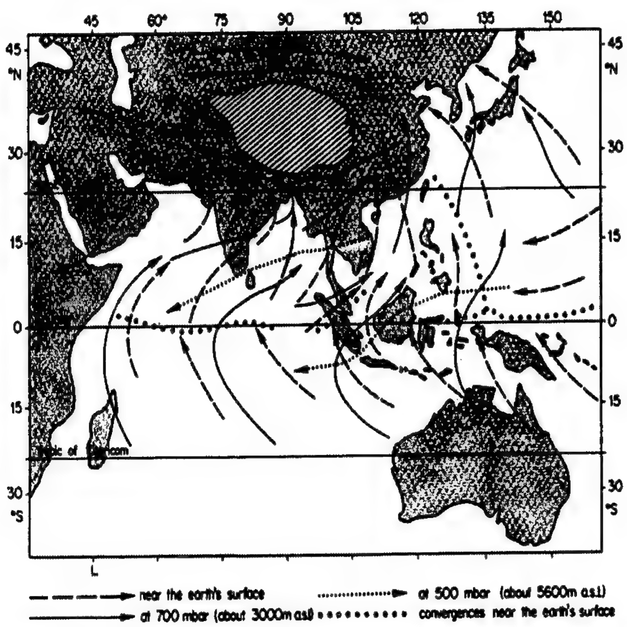


Figure 2-21. Circulation Pattern of the Asian Southwest Monsoon. June to September wind flow patterns are depicted by the arrows while dots represent convergence zones. (McGregor and Nieuwolt, 1998)

Over India, however, prevailing westerlies near 26,000 feet delay the development of the southwest monsoon. By late May, the westerlies suddenly shift north of the Tibetan plateau. This shift allows the upper-air trough to move west and position itself along 75° E. This allows the upper-air easterlies to settle over northern India and opens the way for the southwest monsoon at the lower levels.

Onset. The onset of the southwest monsoon begins the rainy season for South Asia. It starts over the southeastern Bay of Bengal in the middle of May. From there it moves slowly northwestward until it covers all of India by the middle of July (see Figure 2-22). Indian meteorologists make the arrival of the southwest monsoon "official" when it reaches Kerala in southwest India. The arrival of The features associated with the arrival of the southwest monsoon are as follows:

- The westerlies south of the ET are strong, on the order of 20 knots.

- Deep westerlies extend to at least 20,000 feet above sea level.

- The equatorial trough is well-defined on synoptic charts. It sometimes develops a closed low or depression.

- There is heavy rain accompanied by heavy thunderstorms. Rainfall totals along the west coast of India are around 4 inches (102 mm) in 24 hours.

It is difficult to determine monsoon onset and follow its advance through the region. The biggest problem is the monsoon does not advance, remain, or retreat uniformly. It fluctuates greatly in position and intensity when it advances as well as after it establishes itself over a region. As it advances, the monsoon shows all of the features of the ET listed above at some locations, while at other locations, one or more may be missing. The monsoon will sometimes weaken after it establishes itself. Pre-monsoon flow may return and make it difficult to determine if the monsoon is still there.

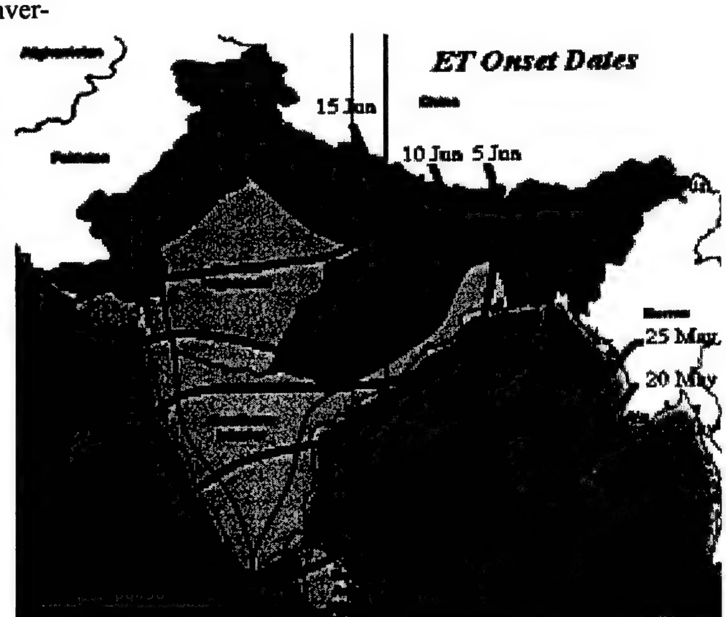


Figure 2-22. Mean Onset Dates of Indian Southwest Monsoon. (Adapted from Hastenrath, 1988 after Das, 1972)

Withdrawal. The southwest monsoon loses most of its force by the end of August, especially in the northernmost regions of the subcontinent. The transition to the northeast monsoon circulation is ready to begin. The equatorial trough retreats south as the subtropical ridge re-establishes itself over northwest India. The monsoon withdraws from northern India by early September (see Figure 2-23). Thunderstorm activity is considerable during the withdrawal. Heavy rain and thunderstorms are sometimes referred to as the southwest monsoon's "last kick." Early morning fog after the previous evening's thunderstorm may signal the monsoon's end.

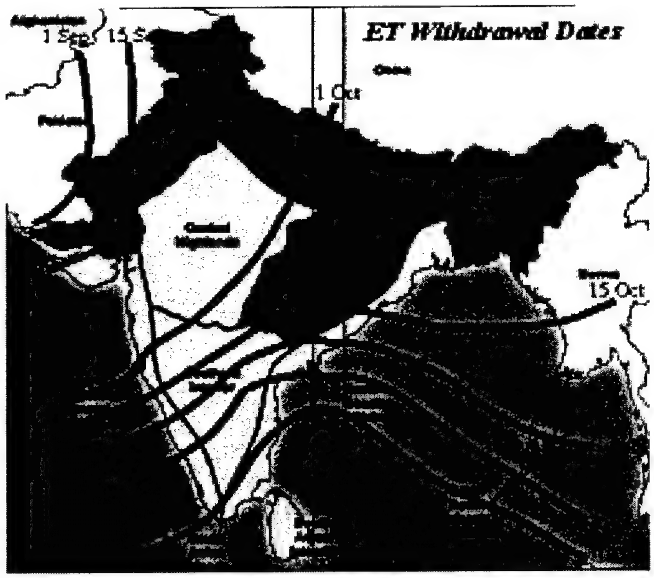


Figure 2-23. Normal Dates of Withdrawl of Southwest Monsoon. (Adapted from Hastenrath, 1988 after Das, 1972)

Onset Vortex. The "onset vortex" is a cyclone associated with the arrival of the southwest monsoon over the Indian Ocean. It normally develops between mid-May and mid-June in the eastern Arabian Sea or the Bay of Bengal. The disturbance resembles, and can become, a tropical cyclone. Formation begins at the mid-tropospheric level, usually at 700 mb, then intensifies downward to the 850-mb level with strong low-level convergence. Strong zonal flow (westerlies produced by the Somali jet) develops before the onset vortex. The disturbances are 200-500 miles (320-800 km) across with a life span of 3-10 days. Surface winds near the storm's eye can reach 50 knots or greater. Researchers differ on the relationship between the onset vortex and the southwest monsoon. Some believe the vortex is a trigger. Other believe it is a response to the southwest monsoon's movement towards the Asian land mass. Figures 2-24a-c show the 850-mb flow before, during, and after the "onset vortex" that developed in 1979.

Monsoon Breaks. The southwest monsoon covers

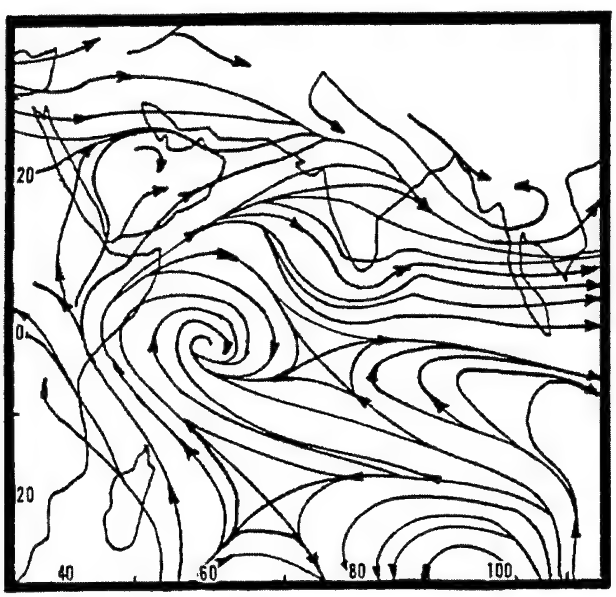


Figure 24a. Streamline Chart (850 mb), 23 May 79/ 1200Z. Depicts low-level flow prior to Onset Vortex. (Krishnamurti, et al, 1981)

Figure 24b. Streamline Chart (850 mb), 17 Jun 79/ 1200Z. Depicts low-level flow during Onset Vortex (C). (Krishnamurti, et al, 1981)

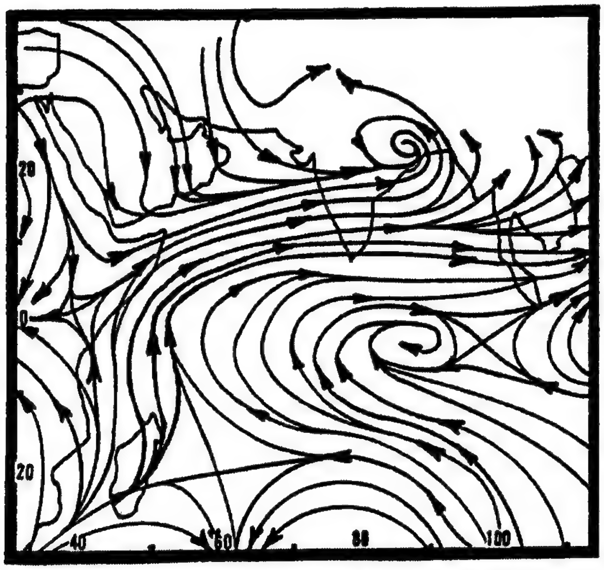


Figure 24c. Streamline Chart (850 mb), 27 Jun 79/ 1200Z. Depicts low-level flow after the Onset Vortex. (Krishnamurti, et al, 1981)

all of India by the end of June. During July and August, the peak intensity period, the monsoon does not maintain uniform or even nearly uniform intensity in terms of rainfall over the country. These variations in rainfall are joined by variations in the synoptic scale weather patterns. When there is low rainfall activity, a "*break*" in the monsoon occurs. Monsoon breaks vary in both intensity and duration. Two of the synoptic situations leading to them involve an ET shift to the north.

- If the western end of the equatorial trough shifts north, a monsoon break is relatively short-lived, about 2-3 days. This occurs when a western disturbance (a low pressure system) moves across the western Himalayas. When it happens, there is excessive rainfall over the western Himalayas and deficit rainfall over the plains of northwest India.

- If the eastern end of the equatorial trough shifts north, a break of 4-5 days is likely. This occurs with the movement of a monsoon depression from the northern Bay of Bengal to Assam. Excessive rain falls in the foothills of the eastern Himalayas and sometimes leads to floods along the rivers of northeast India. At the same time, rain becomes scarce over the plains of Uttar Pradesh, Bihar, Madhya Pradesh, Orissa and Gangetic West Bengal.

Other situations that may lead to a monsoon break inlude the following:

- Development of a warm temperature anomaly over central India, and a cold temperature anomaly over northwestern India.

- One or two low pressure waves move westward across the south Bay of Bengal, and possibly southern India, in the lower and middle troposphere.

- A ridge appears over central India in the lower troposphere.

- The Tibetan anticyclone weakens and moves northeast.

- Blocking highs develop over north Asia along with mid-latitude troughs that extend to lower than normal latitudes. This leads to a series of lows that may move eastward across extreme northern India.

- Monsoon depressions do not occur over the northern portions of the Bay of Bengal.

- Moisture is confined to very low levels where specific humidity decreases from the bottom to top at a relatively fast rate. Convective instability increases, and rains, if any, tend to be convective in nature.

Even though the above listed features have occurred during a monsoon break, research indicates none are absolute indicators a monsoon break is ready to occur.

Monsoon breaks occur most often in the middle of August although they can occur anytime during July and August. The southwest monsoon can and does weaken during June and September, but these events are not considered to be "breaks." During June, the monsoon may not have totally established itself over the entire region, thus a break is not possible. In September, any weakening of the southwest monsoon is regarded as part of the withdrawal phase. There are more monsoon break days in the middle of August than any other ten-day period, and August breaks last slightly longer. If the monsoon break has been intense and long, a gradual recovery of the synoptic conditions to a normal pattern occurs. There are two situations that can hasten the recovery:

- A monsoon depression develops over the Bay of Bengal.

• A low-pressure wave moves west across southern India from the Bay of Bengal. This wave intensifies during or after its passage, becomes a low pressure area or depression, and moves north-northwest along India's west coast. In its wake, the pressure gradient builds up to its normal value.

Equatorial Westerlies. This wind band is formed by the outflow of the South Indian Ocean high and is enhanced by the Somali jet. It extends along the north side of the equator from near the African coast eastward to 130° E. In summer, it is strengthened around 110°E by outflow of the Australian high. This westerly flow extends from the surface to 700 mb, but in July, its strongest month, it extends to 500 mb (see Figure 2-11). The equatorial westerlies are a source of cool, subsiding air between the northern and southern monsoon boundaries. East-moving waves form in this flow.

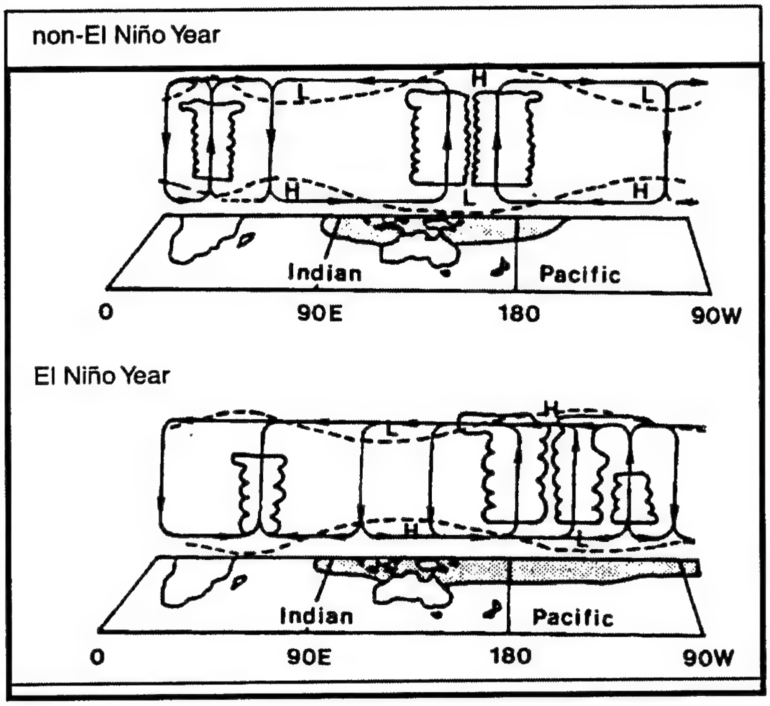


Figure 2-25. Equatorial Circulation Model during El Nino and Non-El Nino Years. Sea-surface temperatures are above 81°F (27°C) in shaded areas. (Fein and Stephens, 1987)

Southern Oscillation (El Niño, La Niña). Also known as the Walker circulation, the southern oscillation is a complex global atmospheric and oceanic phenomenon. It is an important circulation mode of the tropical atmosphere characterized an air exchange between the eastern and western hemispheres. It involves periodic changes in atmospheric pressure, sea-surface temperature, and air temperature. There are two phases to the southern oscillation, a warm "El Niño" and a cold "La Niña," with intervening transitions. The time to complete one cycle varies between 2 and 10 years and averages 3 years. Atmospheric circulation changes that occur near the equator and in association with these phases are shown in Figure 2-25. These changes have significant impact on the climate of the Asian subcontinent.

Figure 2-26 shows the southwest monsoon rainfall totals over India for the period 1871 to 1978. The figure shows the rain amount that falls from June through September.

Values outside one standard deviation of the mean are considered significant departures from normal. Severe floods or droughts result from these departures. Researchers found a strong relationship between rainfall and the southern oscillation. A high southern oscillation index (SOI) generally led to excessive rain while a low

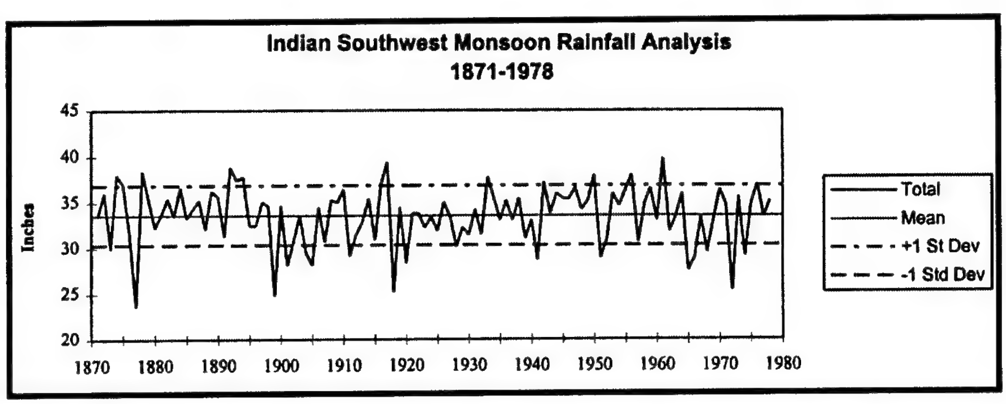


Figure 2-26. Southwest Monsoon Rainfall (June to September) of India. Taken as one unit, these amounts represent 78 percent of annual total. (Pant and Kumar, 1997 from Mooley and Parthasaranthy, 1983)

SOI usually resulted in drought. La Niña events are associated with a high SOI, and El Niño events are associated with a low SOI.

Note: The southern oscillation index (SOI) is based on the sea-level pressure difference between Darwin, Australia and the island of Tahiti. It is obtained by subtracting Darwin's sea-level pressure from Tahiti's (Tahiti minus Darwin). Researchers derived this index after noting a strong, but negative correlation between the sea-level pressure values at the two locations (see Figure 2-27). They found that if the pressure was high at Darwin, it was correspondingly low at Tahiti, and visa-versa. A high SOI (positive) value means sea-level pressure is lower over the western Pacific and the Indian Oceans than the eastern Pacific. A low SOI (negative) value means the opposite.

El Niño. The El Niño phase averages 18 months. It begins with elevated sea-surface temperatures in the eastern Pacific, usually in December (hence the term "El Niño," which means "Christ Child"). These temperature anomalies gradually diminish as they propagate westward, however, and temperatures in the western Pacific Ocean are 3-5 Fahrenheit (2-3 Celsius) degrees lower than normal. These lower temperatures are linked to changes in the monsoon over India. Other atmospheric changes associated with the southern oscillation are not fully understood, but El Niño appears to be connected to variations in sea-surface temperatures in the Atlantic Ocean.

The El Niño begins to appear in the western Pacific during March and April. It reaches peak intensity during the southwest monsoon and lasts into the northeast monsoon. Radical changes to the monsoon system occur during an El Niño year. The North Pacific high strengthens and shifts unusually far south during the southwest monsoon. The high covers a larger area and extends further west. Over the Indian Ocean, the Walker circulation (zonal winds) weakens while the Hadley circulation (meridional winds) strengthens. This results in a weakening or reversal of the easterly wind flow over the Indian Ocean and prevents the movement of tropical disturbances into the Bay of Bengal from the western Pacific. In normal years, these tropical disturbances generate much of the rain that falls on eastern India and Bangladesh during the southwest

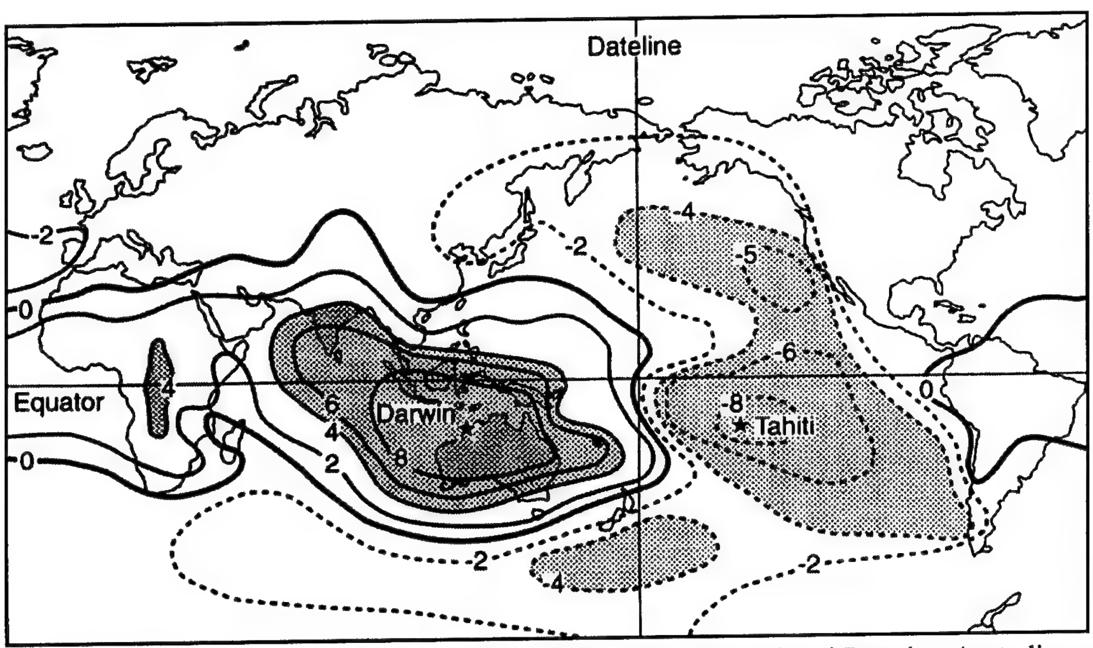


Figure 2-27. Southern Oscillation Pressure. The island of Tahiti and Darwin, Australia are considered to be at the opposite ends of the Walker circulation. As a result, the sea-level pressure difference between them is used to measure the southern oscillation. The numbers represent a statistical measure called the correlation coefficient. They show the pressure variation at Tahiti is inversely related to the variataion at Darwin as are locations near to Darwin. (Adapted from Hastenrath, 1991 and Trenberth, 1984)

monsoon. Also, the ET is usually weaker than normal during an El Niño cycle. It lies south of its normal position, especially during the early stages.

South Asia can expect a drop in precipitation during an El Niño, especially during the southwest monsoon. An analysis of 22 strong and moderate El Niño events between 1871 and 1978 indicated below normal rainfall occurrences during the southwest monsoon during 17 of those events (see Table 2-1). Of the 17 years of below normal rainfall, eight showed a drought occurred. A drought over India is said to occur when the all-India southwest monsoon rainfall is more than 12.5 percent below normal. A strong El Niño event occurs when the positive sea-surface temperature anomalies off the coast of Peru exceed 5 Fahrenheit (3 Celsius) degrees. For a moderate event, the anomalies exceed 3 Fahrenheit (2 Celsius) degrees.

As the transition towards the northeast monsoon begins, rainfall over some areas of the region returns to normal. In some years, rainfall is above normal. Studies indicate Sri Lanka and extreme southern India have normal or above normal rain during the post-monsoon season (October-December) of an El Niño year. During the post-monsoon season of an El Niño year, researchers note tropical cyclones tend to move along a more west-to-southwest track towards southern India and Sri Lanka. Normal movement is towards the west and northwest.

La Niña. When a La Niña is underway, conditions over South Asia tend to be the opposite of those during an El Niño. The Walker circulation strengthens and the Hadley circulation weakens. The equatorial trough is stronger and more active than normal. Above normal rainfall can be expected during the southwest monsoon. Some areas can expect excessive rain that leads to flooding. Historically, almost all of the significant flooding events over the Indian subcontinent occurred during a La Niña. Rainfall patterns during the post-monsoon season (October-December) of a La Niña are also opposite those of an El Niño. This is particularly true for Sri Lanka and the southeastern portion of India where below normal precipitation can be expected. This results from the ET remaining north of Sri Lanka for most of the post-monsoonal season.

Table 2-1. Summary of El Niño Years and All-India Southwest Monsoon Rainfall. Normal rainfall is 33.61 inches with standard deviation of 3.27 inches (S = strong and M = medium). (Mooley and Parthasaranthy, 1983)

		All-India Summer Monsoon Rainfall		
Year	El Niño Intensity	Amount (in)	% Departure from Normal	Category
1871	M	33.32	-0.9	Below Normal
1877	S	23.79	-29.2	Drought
1880	M	32.18	-4.3	Below Normal
1884	S	36.61	8.9	Excess
1887	M	35.32	5.1	Above Normal
1891	S	31.09	-7.5	Below Normal
1896	M	32.47	-3.4	Below Normal
1899	S	24.75	-26.4	Drought
1902	M	31.17	-7.3	Below Normal
1905	M	28.17	-16.2	Drought
1911	S	28.88	-14.1	Drought
1914	M	35.42	5.4	Above Normal
1918	S	25.54	-24.0	Drought
1925	S	31.63	-5.9	Below Normal
1929	M	32.28	-4.0	Below Normal
1939	M	31.07	-7.6	Below Normal
1941	S	28.72	-14.6	Drought
1953	M	36.24	7.8	Above Normal
1957	S	30.90	-8.1	Below Normal
1965	M	27.85	-17.2	Drought
1972	S	25.74	-23.4	Drought
1976	M	33.68	0.2	Above Normal

Synoptic Features

Non-Tropical Features.

Fronts. Fronts transit northern India during the northeast monsoon when lows move in from the northwest. A warm front may be seen ahead of the low while a weak cold front trails. Thunderstorms may accompany the cold front. Well-defined highs rarely follow these lows.

Western Disturbances. These are northeast monsoon migratory lows that move east across northern India. They occur between November and May but are most frequent in December through April. Some originate in the North Atlantic Ocean and Europe, make their way eastward, usually via the

Mediterranean Sea, then move into the region from the Caspian Sea. After moving into India, these systems travel eastward along the southern periphery of the Himalayas. Some may reach far northeastern India. The low tracks generally remain north of 20° N (see Figure 2-28). Sometimes, a weak low develops in a lee-side trough along the eastern slopes of the Sulaiman Range of central Pakistan. This low tends to move east-northeastward into India. From there, it moves east along the same routes taken by other migratory lows. About 4 to 7 disturbances per month move across northern India between December and April. In November and May, the number of disturbances drop to 2 per month. Precipitation from these lows is usually rain over the lowlands and snow over the mountains.

Coastal Trough. A weak pressure trough often develops off the southwest coast of India during the southwest monsoon. It forms near 13°-15° N and shifts north, though it may appear and disappear in place anywhere along the coast. This trough strengthens the southwest monsoon rainfall in the adjacent coastal region.

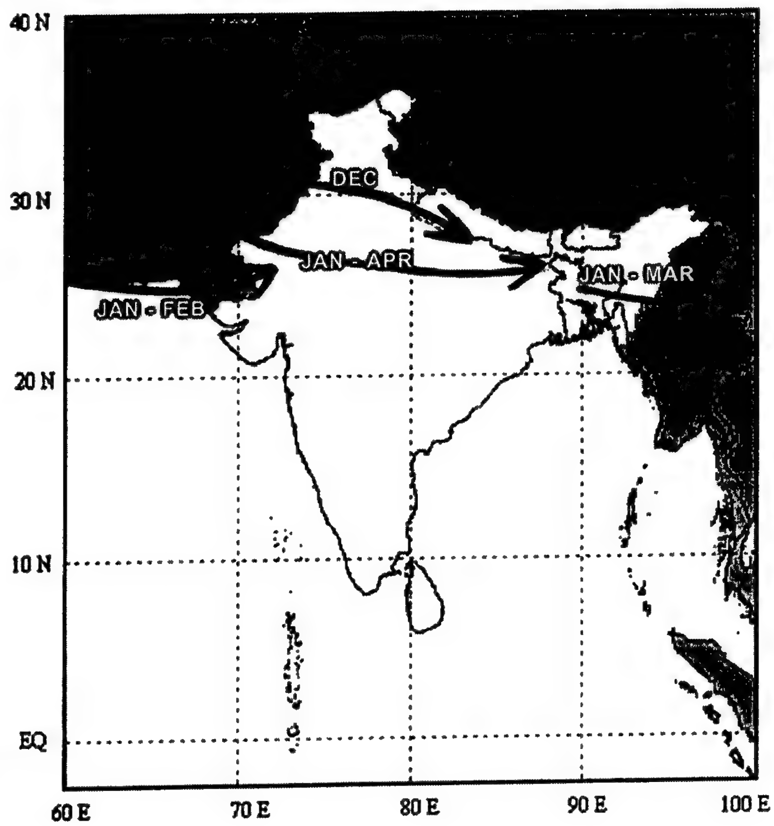


Figure 2-28. Principal Tracks of "Western Disturbances." These systems travel eastward along the southern periphery of the Himalayas. (Adapted from Pant and Kumar, 1997)

Tropical Features.

Tropical Waves. Also known as easterly waves, tropical waves are periodic, west-moving disturbances in the easterly winds. They are most identifiable at low levels as weak pressure troughs with wind shifts. Convergent air occurs toward the rear of the waves and often triggers showers and thunderstorms. The waves travel a mean of 400 miles (640 km) per day. Mid-level winds are lighter than at the surface. Waves are more active when close to the ET.

Tropical Vortices. A vortex is a generic term given to cyclonic cloud and circulation patterns. Quite common in the tropics, some develop into tropical cyclones, but many more dissipate without reaching tropical cyclone intensity. Tropical vortices can be schematically arranged in terms of vertical motion (Figure 2-29). In the fine weather vortices (anticyclones, heat lows, and upper-tropospheric cyclones/cold lows), there is subsidence at the middle-tropospheric levels. For the bad weather vortices (tropical cyclones, monsoon depressions, and mid-tropospheric cyclones), middle-tropospheric air rises.

Monsoon Depressions. These lows play a significant role in the southwest monsoon. They account for much of the rain over India and enhance the monsoonal flow. A monsoon depression is a low that develops over the northern Bay of Bengal north of 17° N during the southwest monsoon (see Figure 2-30). One sometimes develops over the Arabian Sea, but they are more common over the Bay of Bengal. In either region, formation usually takes place near or equatorward of the ET in a strongly baroclinic environment with marked easterly shear.

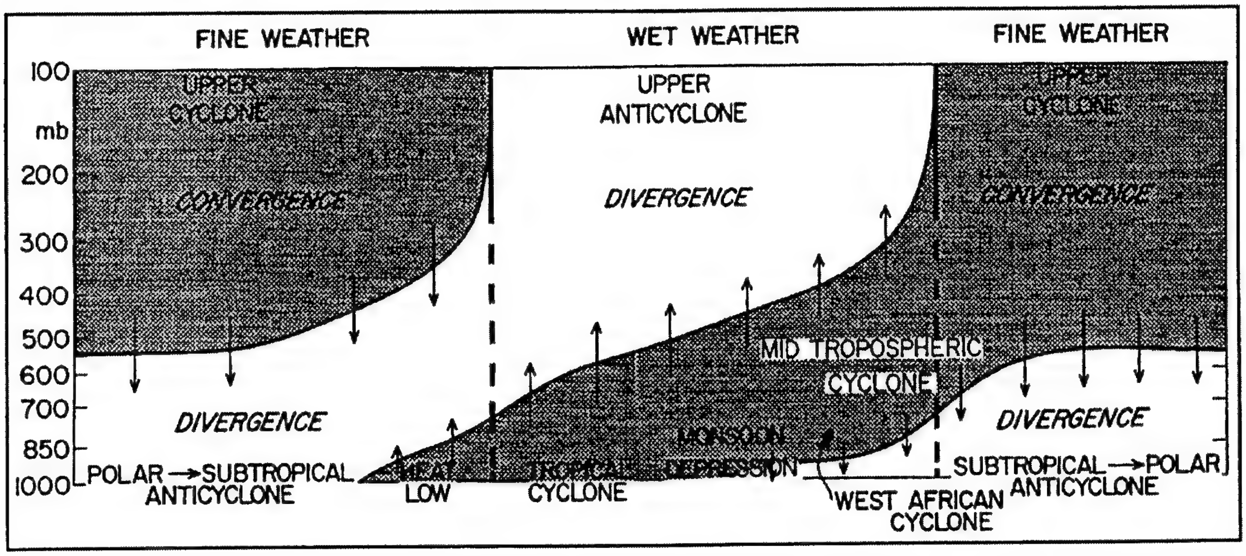


Figure 2-29. Circulation Components of the Atmosphere. Arranged according to weather, divergence, and vertical motion. Solid lines denote levels of non-divergence. (Ramage, 1995)

Origin. The India-Myanmar trough is over the Bay of Bengal during the southwest monsoon. This trough bends southward with increasing height. Tropical waves and disturbances move into the Bay of Bengal from the east. Some disturbances are remnants of western Pacific tropical cyclones. When the tropical wave or disturbance reaches the northern Bay of Bengal, the India-Myanmar trough intensifies. When this happens, a closed low often develops. The trough sometimes intensifies and develops a closed low without a tropical wave or disturbance. This happens less than 15 percent of the time. Within about a day, the low develops into a depression with sustained winds of 22-33 knots. Sometimes the depression develops into a tropical cyclone (sustained wind speeds 64 knots or greater), but this is not likely due to the strong vertical wind shear of the southwest monsoon and its close proximity to the coastline. Intensification to tropical cyclone strength is most likely to occur in September when the vertical wind shear eases as the onset of the transition to the northeast monsoon begins to set up.

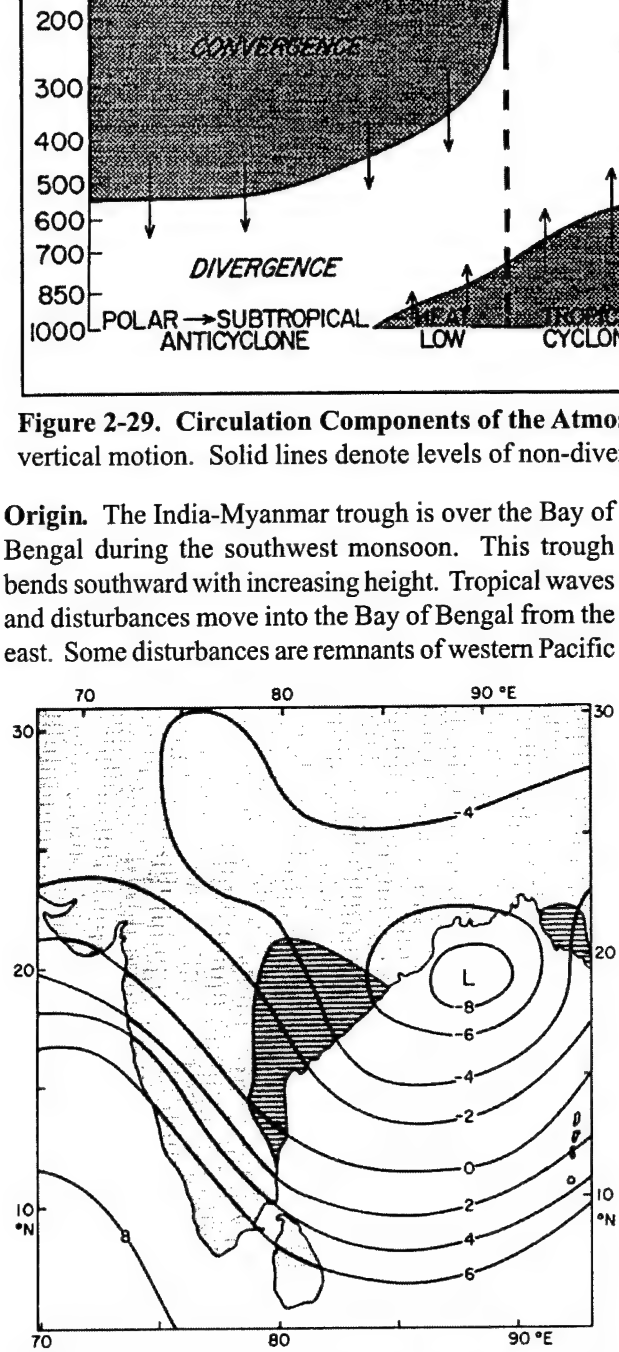


Figure 2-30. Monsoon Depression Example. Analysis of the 1000-mb pressure field over the Bay of Bengal for 1200Z on August 20, 1967. The contours are in decameters. The hatched areas are regions of continuous rain. (Pant and Kumar, 1997 from Hamilton, 1987)

Structure. A monsoon depression is a tropical system, but not a tropical cyclone. It has a cold core near the surface and a warm core in the upper levels (about 500-300 mb). A tropical cyclone, on the other hand, is warm core throughout its entire vertical structure. The monsoon depression's circulation, which can have a diameter of 300-625 miles (500-1,000 km), is strongest at 3,000-5,000 feet. The circulation begins to weaken above 5,000 feet and generally disappears above 300 mb. At the surface, the central pressure is 3-10 millibars below that of the surrounding environment. The center is generally cloud-free. Upward vertical motion is concentrated just south of the surface center (see Figure

2-31). Winds are strongest to the south of the center because of the enhancement of the wind field by the moderate to strong westerlies south of the depression. On satellite imagery, the monsoon depression may resemble a tropical cyclone depression in a stage well before an eye forms.

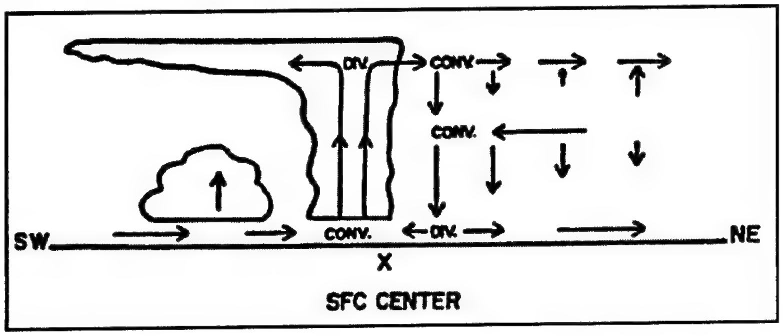


Figure 2-31. Schematic Drawing of the Vertical Circulation across a Monsoon Depression. The asymmetrical cloud field around a depression is attrubuted to the large horizontal wind shear in the vertical. (Ramage, 1995 from Douglas, 1987)

Frequency and Duration. The number of monsoon depressions that develop over the Bay of Bengal varies from year to year, but around 2 per month can be expected between June and September. They occur more frequently in the latter part of the southwest monsoon (see Figure 2-32). The average life span is 4-6 days; some last as long as 10 days.

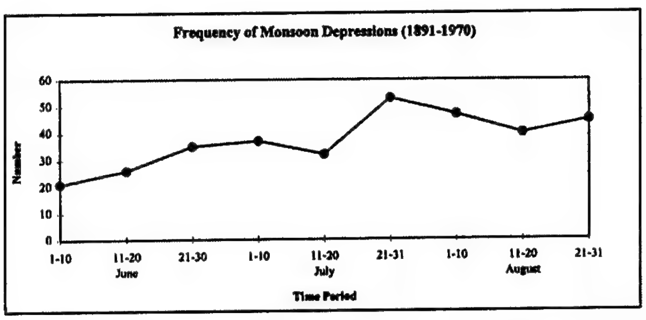


Figure 2-32. Temporal Distribution of the Number of Monsoon Depressions in the Bay of Bengal during June - August. (Adapted from Rao, 1976)

Movement. Once a monsoon depression forms, it moves west-northwest with the upper air flow along one of two tracks (see Figure 2-33). Track A is followed by the depressions once the southwest monsoon establishes itself over northern India. After moving onshore and across central India, the monsoon depression generally weakens in intensity as it is cut off from its moisture supply. It then moves towards the west-northwest and merges with the Asiatic low. Occasionally, the depression gains a fresh moisture supply from the Arabian Sea. The depression reintensifies and takes a more westwardly track. It eventually reaches Gujarat in western India and dumps heavy rain over that region. A mid-latitude westerly trough will sometimes induce a west-moving depression to recurve to north, then north-northeast. This depression moves into the Himalayan mountains and dissipates with very heavy rainfall over the mountain slopes. It is also possible for north-moving depressions to shift the ET northward where it settles against the mountains. This causes a monsoon break.

Rainfall. Widespread heavy rainfall is common with monsoon depressions. The amount of rainfall depends on a number of factors:

- Intensity of the depression.
- Vertical velocity in the different sectors of the depression's circulation.
- Moisture content of the air around the depression, which has to be continuously renewed and replenished.
- Topography.
- The state of the depression, i.e., is it developing or dissipating?
- Whether or not the system is recurving.

For monsoon depressions that move towards the west or northwest, most of the rain falls over the southern and southwestern sectors of the low. The heaviest rainfall generally occurs in the southwestern sector away from the center. The wind field around the monsoon depression is asymmetrical (see Figure 2-34). This results in a strong horizontal velocity convergence zone south of the line CP. This convergence zone causes the heaviest rainfall to occur in the southwestern sector of the depression.

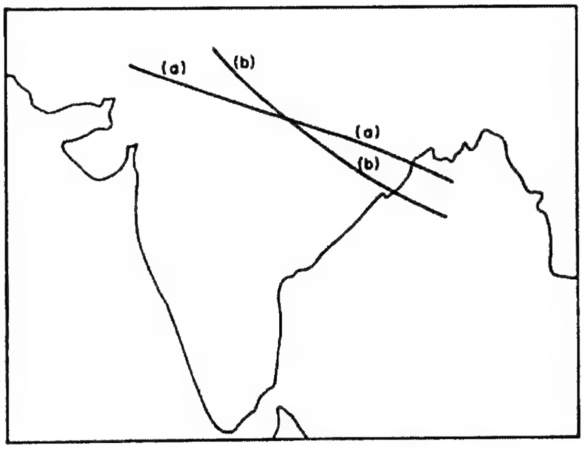


Figure 2-33. Monsoon Depression Tracks. Track A is followed by the depressions once the southwest monsoon establishes itself over northern India. Track B is followed during early June when the monsoon is getting established and during late September, when the southwest monsoon begins its withdrawal. (Asnani, 1993)

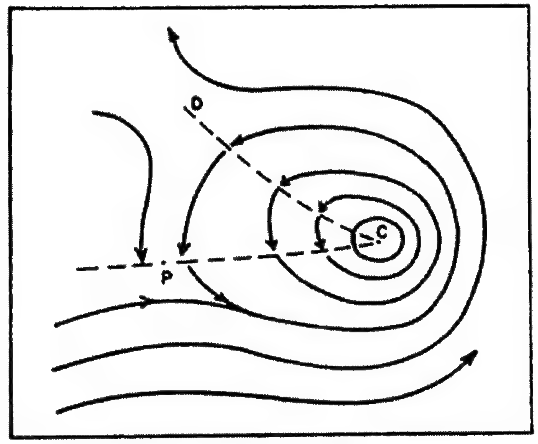


Figure 2-34. Wind Field of a Monsoon Depression. Two lines of discontinuity are seen in the wind directions, one extends westwards (line CP), the other extends northwestward (line CD). The northerly and westerly air currents around the depression meet near point P. (Asnani, 1993)

If a monsoon depression recurves to the north or northeast in advance of a mid-latitude trough, the zone of maximum rainfall will shift to the northern sectors after recurvature. A strong, horizontal velocity convergence zone is created along the leading edge of the mid-latitude trough between the monsoon depression's center and the Himalayas. The heaviest rains fall on the slopes of the Himalayas in advance of the depression.

Researchers have been studying the monsoon depression and have drawn conclusions on their rainfall patterns:

- The immediate vicinity of the depression's center and the outer periphery of the circulation field area are generally free of heavy rainfall.

- For westward-moving depressions, the heaviest rainfall occurs in the southwest quadrant, about 125-250 miles (200-400 km) from the center. A secondary zone of maximum rainfall lies about 500 miles (800 km) west of the center.

- Rainfall amounts of 12 inches (305 mm) or greater in a 24-hour period occur quite often in monsoon depressions and cause serious flooding.

- Heavy rainfall in the rear sector of a monsoon depression occurs in only exceptional cases.

- When a monsoon depression moves west of 80° E, the rainfall amounts increase considerably. This may be, at times, 200 percent of that normally received. This is due to the depression being reintensified by the Arabian Sea branch of the southwest monsoon.

Effects on the Indian West Coast. When a monsoon depression forms in the northern Bay of Bengal, India's west coast tends to see an increase in rainfall. In 70 percent of the monsoon depressions studied between 1956 and 1975 (111 cases), a monsoon depression in the Bay of Bengal leads to a strengthening of the southwest monsoon flow in the Arabian Sea. This results in a rainfall increase along the west coast only if an active coastal trough develops or exists along India's west coast. This trough allows cyclonic circulation (mid-tropospheric cyclone) to develop over the northeastern Arabian Sea and the adjacent land areas between 850 and 700 mb. The Somali jet and the low-level winds strengthen, and when coupled with the cyclonic vorticity, result in increased rain. The rainfall increase also occurs along the Western Ghats. No appreciable increase in rainfall is noted along the coastline on the southwestern tip of India.

Mid-Tropospheric Cyclones. These systems develop during the southwest monsoon between the 700 and 500 mb. The northeast Arabian Sea near the equatorial trough is the favored location for development in the Indian Ocean. The mid-tropospheric cyclone is hardly detectable near the sea-level or at the 200-mb level, yet it is the major producer of rain along India's western coast. Some characteristics are listed below:

- Essentially stationary; movement, if any, is westward.

- Life cycle about 10 days.

- Maximum wind speed of 40 knots near 600 mb.

- Pronounced warm core above 600 mb; slight cold core below.

- Total rainfall amounts of 7.9 inches (201 mm) per 24 hours are not uncommon.

Figure 2-35 depicts the kinematic analyses of the near-surface and 600 mb of an Arabian Sea mid-tropospheric cyclone observed in 1963. A weak coastal trough is the only sign of a surface disturbance while a well-developed cyclone exists at 600 mb. Figure 2-36 shows the vertical motion and cloud distribution associated with the mid-tropospheric cyclone, and Figure 2-37 shows its horizontal cloudiness and rainfall distribution.

Tropical Cyclones. These synoptic-scale storms pose a serious threat to the north Indian Ocean, especially the Bay of Bengal. When it comes to storm surges, the Bay of Bengal is the most dangerous tropical cyclone basin in the world. Not only are its physical characteristics conducive to very large storm surges, its low-lying coastal regions are heavily populated.

Tropical cyclones develop over tropical waters and have well-organized circulations. They usually develop from pre-existing disturbances and intensify into the following categories:

- Tropical Depressions. These are the weakest tropical cyclones with sustained wind speeds near the center less than 34 knots. Minimal wind damage occurs, but heavy rainfall can cause flooding.

- Tropical Storms. These are tropical cyclones with sustained wind speeds of 34-63 knots near the center. Significant wind damage to poorly designed or constructed structures and major flooding occurs.

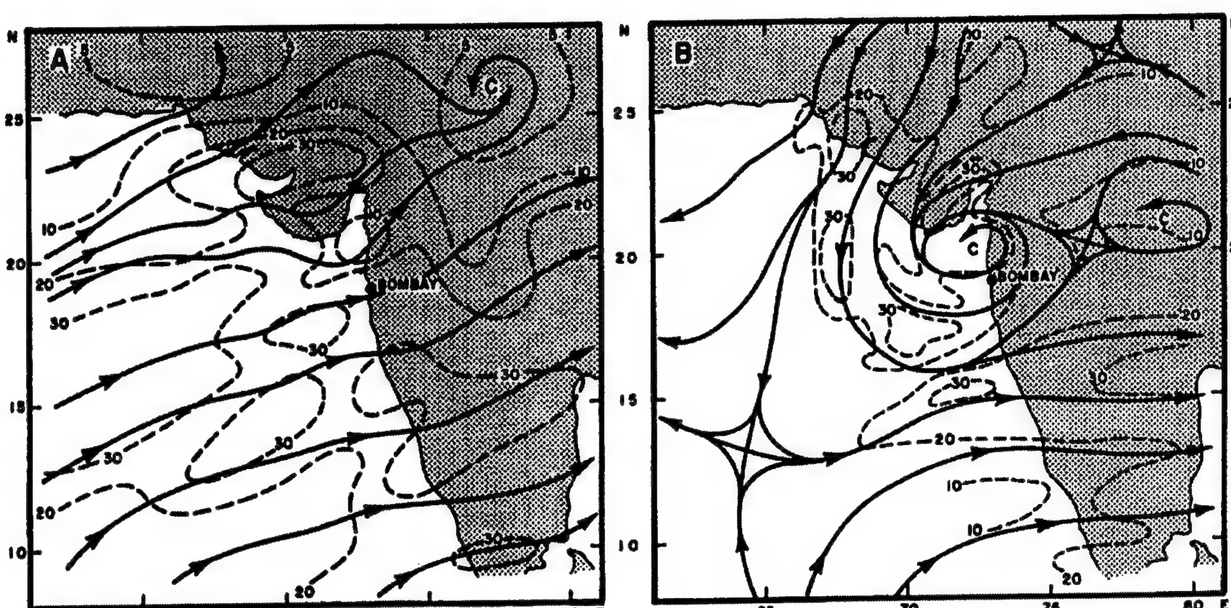


Figure 2-35. Arabian Sea Composite Kinematic Analyses (Knots) for 1-10 July 1963. (A) depicts the near surface layer (1600 to 3000 feet/500 to 900 meters); (B) is the 600-mb level, showing a well-developed mid-tropospheric cyclone over western India. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

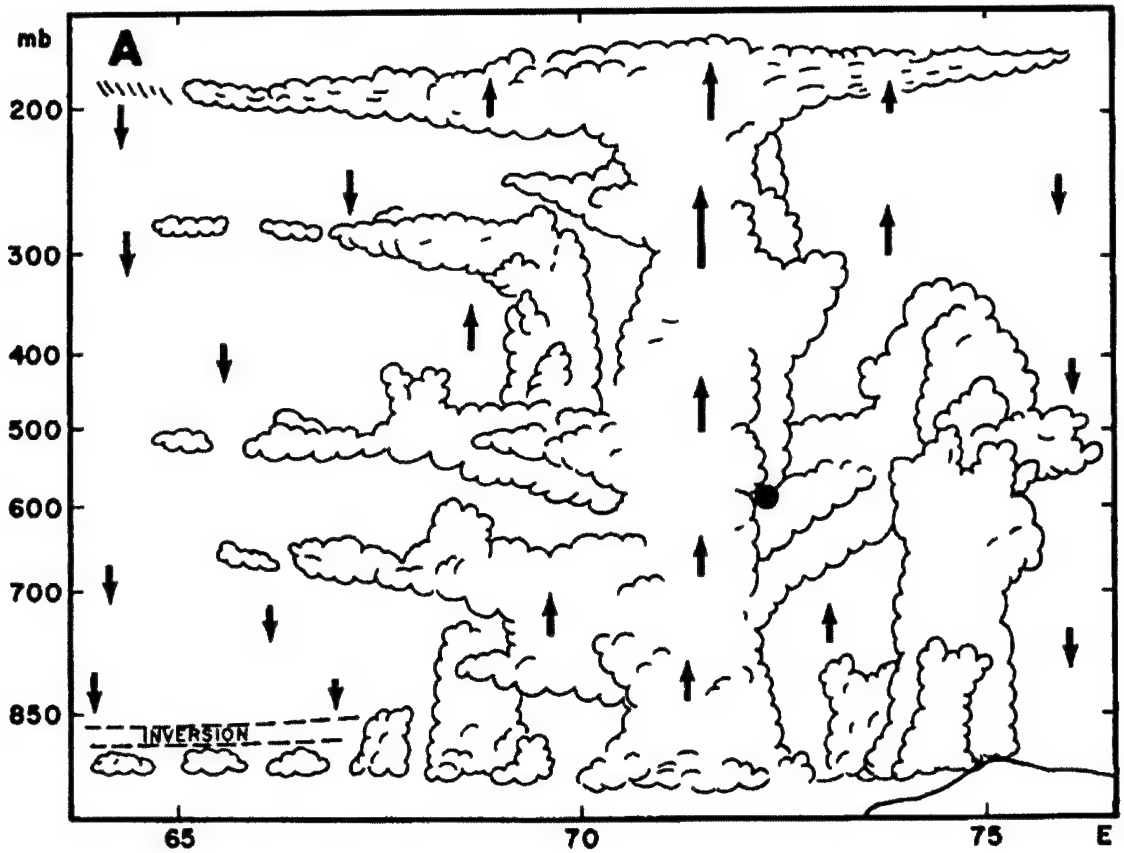


Figure 2-36. Mid-Tropospheric Cyclone Cross-Section. Vertical east-west cross-section of the mid-tropospheric cyclone shown in Figure 2-35. Large dot locates the center at 600 mb. Arrows depict relative vertical motion computed from composite kinematic analyses. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

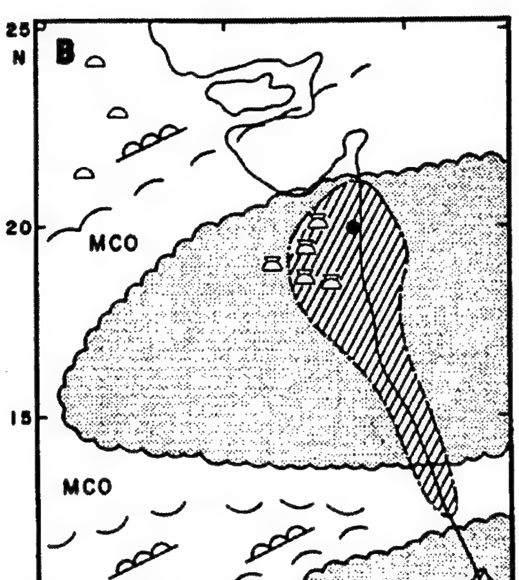


Figure 2-37. Mid-Tropospheric Cyclone Cloud and Rainfall Fields. Horizontal cloudiness and rainfall distribution of the mid-tropospheric cyclone depicted in Figure 2-35. The hatched area delineates rainfall of more than 1.6 inches (41 mm) per day. Shaded areas show broken-to-overcast middle or high cloud coverage. (Ramage, 1995 adapted from Miller and Keshavamurthy, 1968)

- Typhoons. Typhoons, the most powerful tropical cyclones, are known for their destructive high winds, heavy rains, and impressive storm tides. Sustained winds of at least 64 knots are near the center; some typhoons sustain wind speeds over 150 knots. Typhoons with sustained wind speeds of at least 130 knots are called "super typhoons." Extensive to catastrophic wind damage is likely with these storms when landfall occurs. Extensive flooding is likely with heavy rain and high storm tides.

Origin. Tropical cyclones develop in maritime air over the open waters, usually on the equator side of the subtropical ridge axis. Some tropical cyclones in the Bay of Bengal originate in the western Pacific Ocean and the South China Sea. Others form when the remnants of western Pacific typhoons cross Indo-China and regenerate over the Bay of Bengal. Development is most favorable in the vicinity of the ET. Other favorable meteorological conditions are:

- A convectively unstable air mass.

- A sea surface temperature of 81°F (27°C) or greater.

- The presence of positive vorticity.

- A tropical wave in or moving into the area.

- Low-level convergence and upper-level divergence in the area of the disturbance.

- Weak vertical wind shear in the zonal horizontal wind flow.

- Development must occur at least 3 degrees latitude from the equator.

Structure. A tropical cyclone is warm core. The most obvious feature of a mature tropical cyclone is the eye, as seen in Figure 2-38. The eye is normally 6-12 miles (10-20 km) across and coincides with the wall cloud, the location of the most vigorous convection, and heaviest rain in the storm. Inside the eye, skies are generally clear with relatively light winds. The strongest winds of a tropical cyclone are around the center and near the surface and decrease outward. There is cyclonic circulation in the lower levels and anticyclonic circulation aloft. This allows the tropical cyclone to maintain itself through air inflow in the lower levels and outflow at the top. Cut off either and the system will die.

Frequency and Duration. The north Indian Ocean is fairly active, nearly 5 tropical cyclones per year, and most occur over the Bay of Bengal (see Figure 2-39). Figure 2-40 contains a month by month breakdown of tropical cyclone occurrence. Table 2-2 shows the mean monthly occurrence. The data shows a clear seasonal pattern. Tropical cyclones are most likely to develop during the two transition seasons between the monsoons.

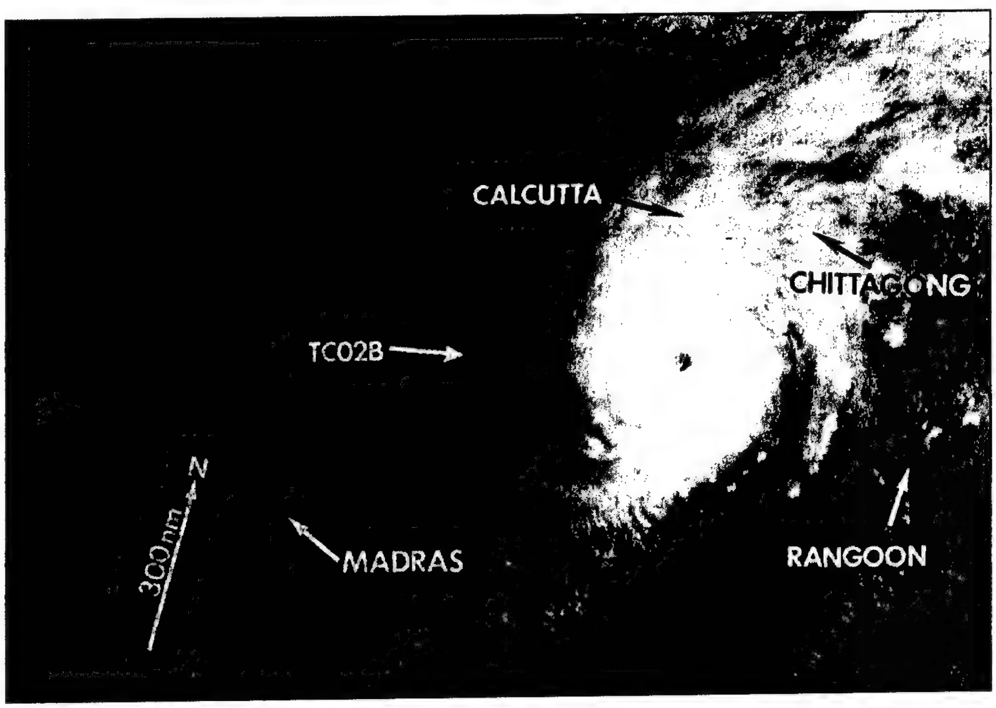


Figure 2-38. Tropical Cyclone 02B in Bay of Bengal. Image of tropical cyclone bearing down on the coast of Bangladesh. Estimated winds were 130 knots. (Courtesy Joint Typhoon Warning Center, 1991)

The late year transition (post-monsoon season) has the annual maximum activity. The equatorial trough lies essentially east-west over the north Indian Ocean from mid-September to mid-December. Its intra-season position varies from near 20° N in late September to around 5° N by early December. As the ET moves south, easterly flow reestablishes itself in the northern portions of the Bay of Bengal and the Arabian Sea while a westerly wind flow exists equatorward of the ET. This creates the ideal low-level circulation pattern for tropical cyclone development. The hot season is the second most active period of tropical cyclone activity. It is shorter than the post-monsoon active period, and its circulation changes are more rapid. As a result, the favorable period for tropical cyclone period is shorter, essentially from mid-April to mid-June.

The mean circulation during the southwest monsoon is not favorable for tropical cyclone development. The ET lies over land, and westerlies cover the north Indian Ocean. The strong, upper-level easterlies over the northern Bay of Bengal create strong vertical shear detrimental to tropical cyclone development. Occasionally, the ET moves south over the northern Bay of Bengal. When this happens, a monsoon depression develops and moves northwest along the ET. Most monsoon depressions do not attain tropical cyclone status before making landfall.

During mid-December to mid-April, the ET lies in the south Indian Ocean or very close to the equator. Both positions are unfavorable for tropical development. The cross-equatorial flow sometimes increases and pushes the ET north to between 5° and 10° N, which makes tropical cyclone development possible. Development doesn't exceed a weak tropical storm.

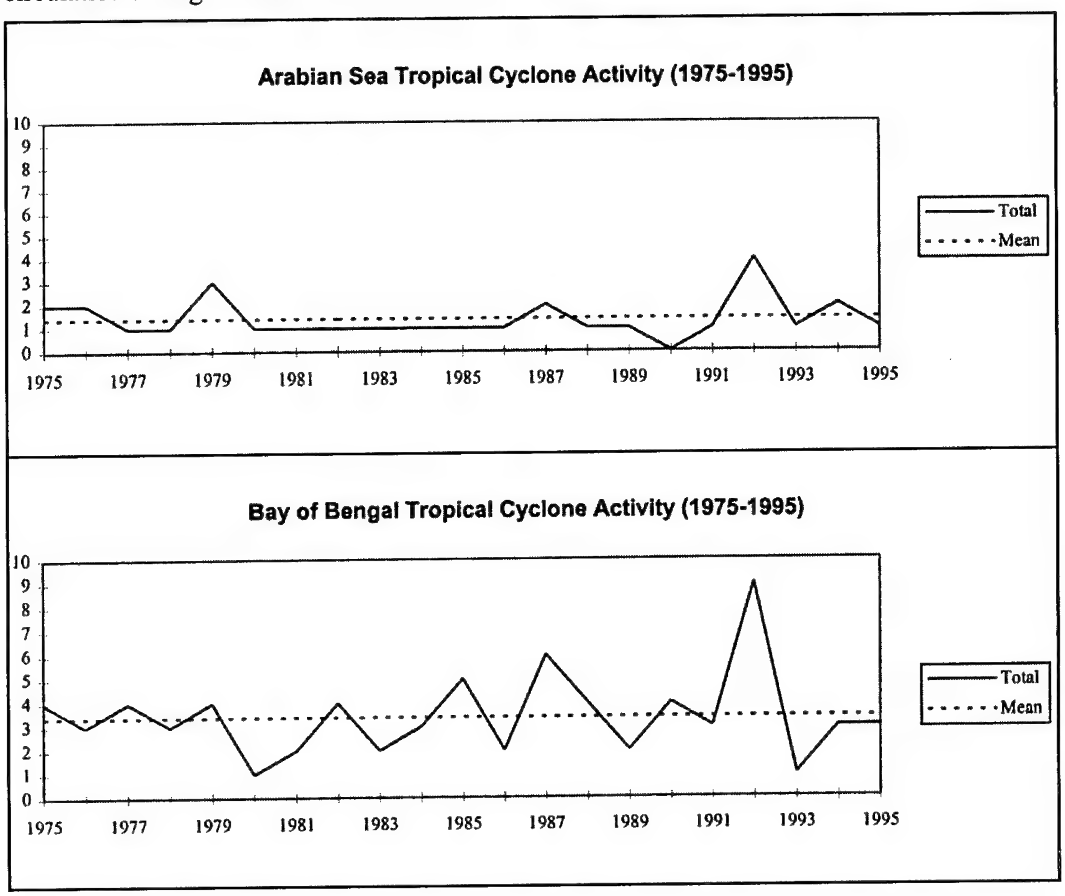


Figure 2-39. North Indian Ocean Tropical Cyclone Activity. Shows yearly total of tropical cyclones over a 21-year period (1975-1995) for the Arabian Sea and the Bay of Bengal. Comparison is made to the mean annual number for the same time period and compares it to mean number over the period. (Adapted from *1995 Annual Tropical Cyclone Report*)

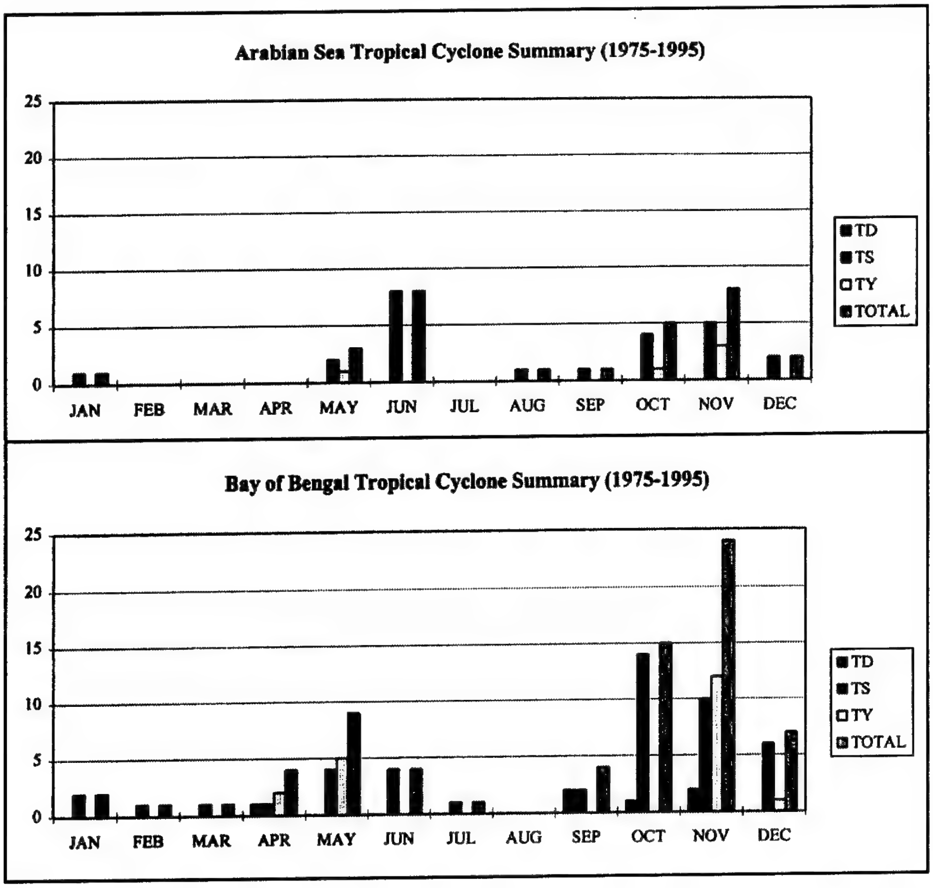


Figure 2-40. Tropical Cyclone Occurrence in the North Indian Ocean. Shows the monthly breakout on the number of tropical cyclones that occurred between 1975 and 1995 in the Arabian Sea and the Bay of Bengal. TD = Tropical Depression (winds $<$35knots); TS = Tropical Storm strength cyclones (winds 35 - 63 knots); and TY = Typhoon strength cyclones (winds $\geq$64 knots). (Adapted from *1995 Annual Tropical Cyclone Report*)

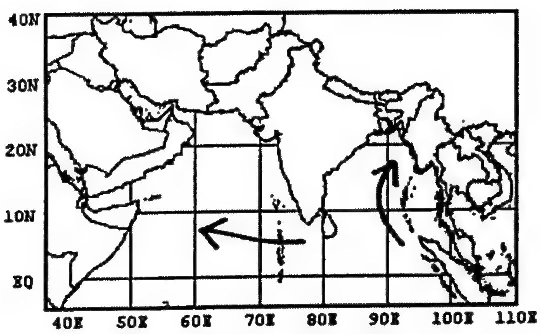
Table 2-2. Mean Tropical Cyclone Occurrence, by Month, for the North Indian Ocean. Period of Record: 1975-1995. Asterisk (*) denotes at least one tropical cyclone occurred. (Adapted from *1995 Annual Tropical Cyclone Report*)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Arabian Sea	*	0	0	0	0.1	0.4	0	*	*	0.2	0.4	0.1	1.4
Bay of Bengal	0.1	*	*	0.2	0.4	0.2	*	0	0.2	0.7	1.1	0.3	3.4
Total:	0.1	*	*	0.2	0.5	0.6	*	*	0.2	0.9	1.5	0.4	4.8

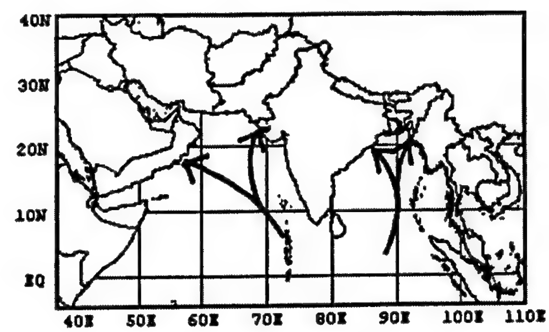
Movement. The tropical cyclone tracks in Figure 2-41 are mean tracks for the given period and are drawn along axes of maximum cyclone frequency. These mean tracks hide the variability of the individual tropical cyclone tracks (Figure 2-42). The environment of a tropical cyclone largely controls its movement. The biggest factor is the position and intensity of the subtropical ridge. Movement in the north Indian Ocean is generally east to west or west-northwest. North movement is possible if there is a weakness in the ridge.

Cloud Features.

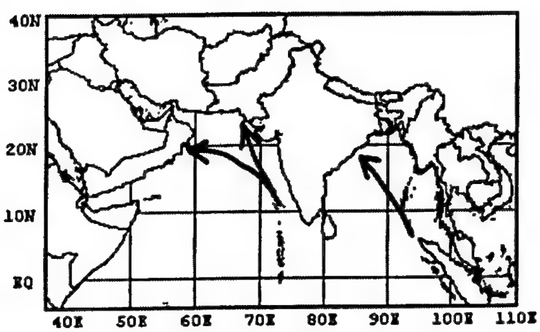
Cloud Clusters. Cloud clusters, the primary cloud feature of the equatorial trough, have extensive stratiform decks with rainfall concentrated in embedded



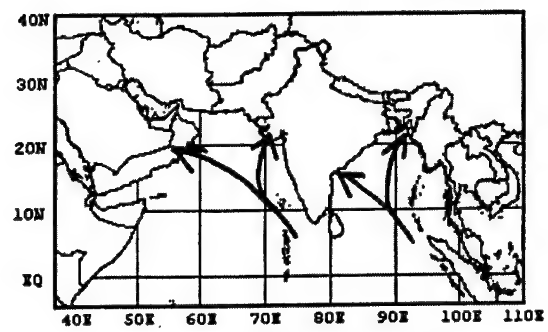
January 1 to April 30



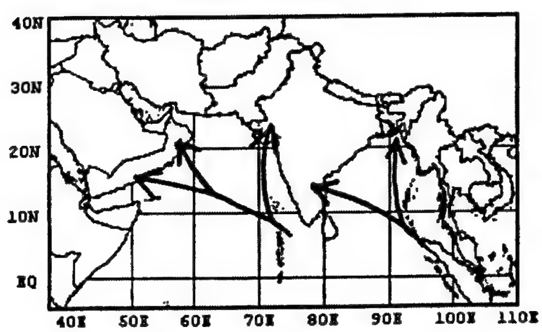
May 1 to July 31



August 1 to September 30



October 1 to November 30



December 1 to December 31

Figure 2-41. Tropical Cyclone Tracks for the North Indian Ocean. The mean tracks (in the five charts) are drawn along the area of maxium tropical cyclone frequency. (Adapted from Pant and Kumar, 1997)

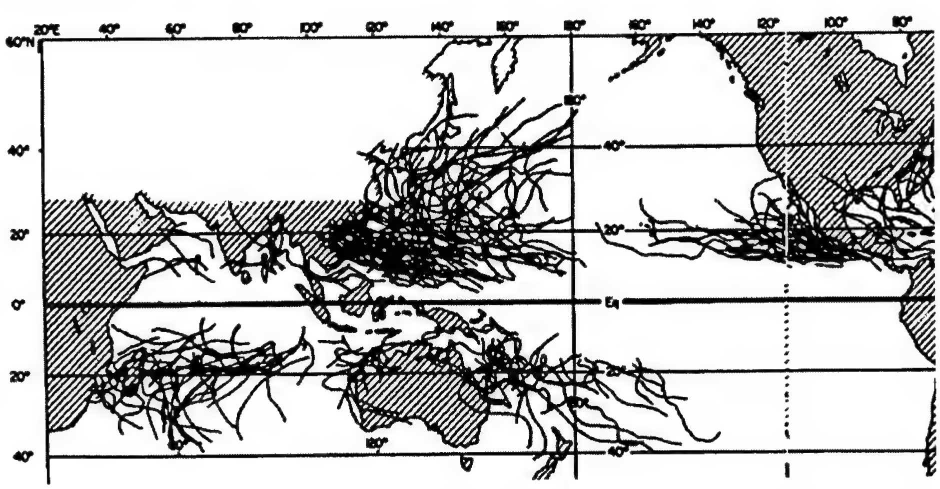


Figure 2-42. Tropical Cyclone Tracks for a 3-Year Period. The figure shows the variability of tropical cyclone tracks. (Ramage, 1995 adapted from Gray, 1978)

convection (Figure 2-43) capped by cirrus shields. They are formed and maintained by steady, low-tropospheric convergence. Cloud clusters last 1-3 days and extend 185-620 miles in diameter. They undergo diurnal intensity fluctuations as they move with the low-level tropospheric wind flow. A few eventually evolve into tropical cyclones. There are two types of cloud clusters, squall and non-squall. A squall cluster occurs with a tropical squall line. It undergoes explosive growth and moves rapidly after forming. On satellite imagery, this cluster has a distinctive convex leading edge. The non-squall cluster occurs most often. It is slow moving and lacks the distinctive oval cirrus shield and arc-shaped leading edge.

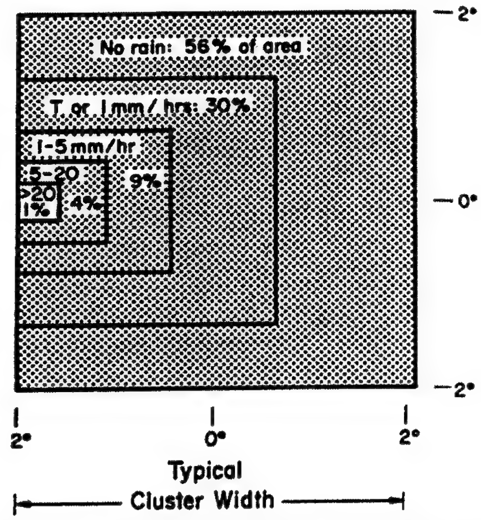


Figure 2-43. Area Distribution of Rainfall Intensity within a Typical Cloud Cluster. Shows the percentage of the horizontal cluster area occupied by various rainfall intensities. It does not mean all rainfall is concentrated in a small quadrant at the leading edge of the cluster. (Higdon, et al, 1997 from Ruprecht and Gray, 1976)

Mesoscale Convective Complexes (MCCs). The tropical MCCs that affect South Asia are most frequent over India and Bangladesh. MCCs develop with the onset and withdrawal of the southwest monsoon. During April to June, most MCCs develop over eastern India and Bangladesh. There is little or no MCC activity over the northwest. MCC activity spreads northwestward as the summer progresses. It occurs over most of the region by late August. MCC development is greatest during July to September. After development, MCCs produce heavy rain and hail. About 40 percent of the rain from tropical MCCs comes from stratiform clouds. Hail formation in tropical MCCs is by riming. It is softer than the hail in MCCs outside the tropics. Although MCCs occur throughout the region, they tend to form mostly over land (see Figure 2-44). The trigger for many is the interaction of convective cells or cloud clusters with a land breeze or a sea breeze front. Others are orographically induced. Some are formed by the interaction of the convective cells with the ET. In those MCCs that form over the open water, convergence of the low-level wind flow is usually the trigger. MCC

Figure 2-44. Mesoscale Convective Complexes over South Asia during 1988. Shows the tracks of MCCs from (a) April to June and (b) July to September. Dots indicate the pregenesis stage; solid lines MCC paths between genesis and dissipation; dashes indicate the dissipating or remnant stage. The circled numbers correspond to the MCC case number and the MCC centroid position at maximum areal extent. The plus (+) signs indicate where an MCC transformed into a tropical or monsoon depression. (Laing and Fritsch, 1993)

movement appears to be with the mean 700-500 mb wind flow. Some, especially those that form over the open water, can intensify into tropical or monsoon depressions. Others sometimes grow until they have dimensions similar to a tropical cyclone. MCCs are predominately nocturnal and have an average life span of 12 hours. Thunderstorms develop first around 1700L. MCC formation usually follows around 2200L, and dissipation occurs between 0700L and 1400L. They usually reach maximum intensity between 0000L and 0600L. Some MCCs, especially those that form over water away from land masses, can last 2-3 days under the right conditions. They still, undergo a diurnal fluctuation in convection.

Mesoscale Weather Events.

Nor'westers. These are lines of severe thunderstorms that frequent northeast India, particularly the lower Ganges River basin (West Bengal) and Bangladesh, in late winter and all of the hot season. They occur as from February to the middle of June. Development takes place when warm, moist, conditionally unstable air that flows up from the Bay of Bengal clashes with cool, dry air that flows down from the Himalayas. The southwest monsoon puts an end to nor'westers as the southerly air flow dominates the subcontinent and prevents the flow of cool air from the north.

Nor'westers generally move from the northwest to southeast. They less commonly move from the north or northeast. Late afternoon or evening on a warm, humid day is the favorite time for development. The storms rarely last more than 3-4 hours and are followed by clear, cool weather. Nor'westers often occur in the same place and around the same time 3 or 4 days in a row. Strong gusty winds, torrential rains, hail and severe lightning accompany these storms. Winds in excess of 85 knots are possible. Nor'westers also spawn tornadoes. As the season progresses, nor'wester activity extends northward and westward, the height of the tops of the thunderstorms increases, and the storms become more severe. but the occurrence of hail decreases. As the pre-monsoon season progresses:

- The ET moves into the Gangetic Plain and intensifies.

- Nor'wester activity spreads to the north and west as the horizontal extent and vertical depth of the maritime air increases northward and westward.

- The cloud condensation level (CCL) lowers during the period. The buoyant energy also increases to allow for greater penetration of the convective clouds into the lower stratosphere.

- As the Tibetan high sets up, wind speeds in the middle and upper troposphere decrease. This reduces vertical wind shear over the region and removes the barriers to thunderstorm development.

Hailstorms. The mean rate of hailstorms over the subcontinental plains is 1 per year or two. The foothills of the Himalayas have the greatest occurrence, but coastal areas south of 20° N and the Gujurat coast are practically hail-free. The plains north of 20° N experience a hailstorm about once every 1-2 years, except for Gujurat and the desert areas where the frequency is lower. The hot season is the period of greatest hail activity. Hail events also occur during the northeast monsoon (dry) season, but to a lesser extent. Hailstorms occur most of the year along the foothills of the Himalayas. The chance for hail diminishes greatly once the southwest monsoon arrives.

Tornadoes. These violent events are called "Hat-ishnura" (elephant's trunk) in northeast India where a majority of them occur over the Indian subcontinent. The Indian Meteorological Department recorded 42 tornadoes between 1951 and 1980 (see Table 2-3). They also reported 113 cases of strong winds associated with severe weather events that caused large scale damage. Of the 42 tornadoes, most (33) occurred during the hot season. Many were spawned by nor'westers. The majority (27), as well as the strongest, occurred in Bangladesh and the lower Ganges River basin (see Figure 2-45). They formed near migratory mesoscale lows along wind discontinuity lines in the lower tropospheric levels. The higher incidence of tornadoes in Bangladesh may be due to the many lakes and rivers of that country.

Dust Storms. These are fairly common in the northern part of the subcontinent during the hot season prior to the onset of the southwest monsoon. Conditions become

Table 2-3. Monthly Distribution of Reported Tornadoes Between 1951 and 1980.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
0	0	7	17	9	2	1	0	4	1	1	0	42

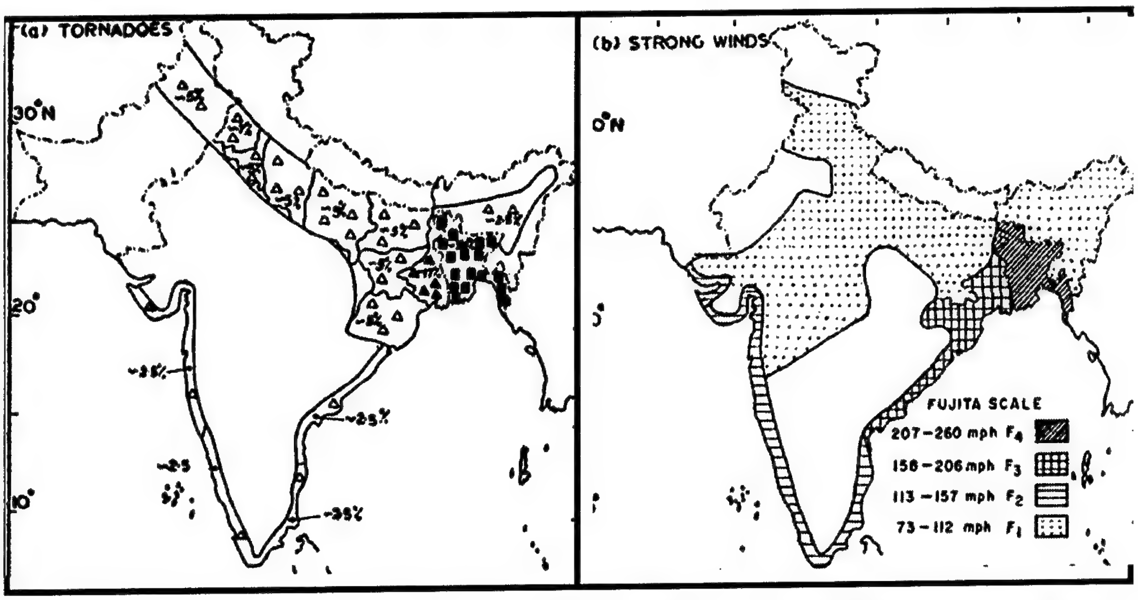


Figure 2-45. Distribution of Tornadoes and Strong Winds over Indian Subcontinent. (Ramage, 1995 adapted from Singh, 1981)

favorable during the long dry season, when vegetation dies and exposes the barren soil. When the hot season sets in, strong, gusty winds pick up the fine, dry soil and carry it to great heights. The Thar Desert has the greatest number of dust storms followed by the upper Ganges plains. Once the southwest monsoon sets up and the rains begin, dust storms in the Ganges plains cease. They reoccur during the southwest monsoon if there is an extended break, such as those in El Niño years.

Diurnal Wind Circulations.

Land/Sea Breezes. Differential surface heating generates daytime sea breezes and nighttime land breezes along the coasts of India and Bangladesh, however, many of the islands in the region do not have sufficient land mass to generate a land/sea breeze environment. With the monsoon wind reversal, land/sea breeze effects change dramatically from season to season. They are more pronounced during the northeast monsoon (November to May). The marine boundary layer, within which the land/sea breeze circulation occurs, rarely extends above 3,000 feet AGL or beyond 19 miles (30 km) inland unless modified by synoptic flow. Two types of land/sea breezes are described below.

- "Common" land/sea breezes affect many coastal areas of India and Bangladesh. Figure 2-46 illustrates the common land/sea breeze circulation along a uniform coastline under calm conditions with no topographic influences. Onshore (A) and offshore (B) flow intensifies in proportion to the daily heat exchanges between land and water. Common land/sea breezes normally reverse near dawn and dusk, with an onshore sea breeze during the day and an offshore land breeze at night. The sea breeze is at maximum strength during the afternoon.

- "Frontal" land/sea breezes occur when a breeze circulation forms in combination with strong flow perpendicular to the coast. In these cases, a boundary, like that in Figure 2-47, forms. This is often linked to low-level jets, shown as heavy arrows in the figure.

Onshore gradient flow enhances the sea breeze; offshore gradient flow strengthens the land breeze and weakens the sea breeze. With offshore flow, the time of the wind reversal is delayed by 1-4 hours as gradient flow keeps the sea breeze boundary layer, or "front," from moving ashore. Under these conditions, the strongest sea breezes occur near midnight, contrary to the norm.

Terrain near the coastline modifies the land/sea breeze in several ways. Orographic lifting produces sea breeze-stratiform/cumuliform cloudiness over higher terrain, while nocturnal downslope winds from the mountains accelerate the land breeze over water. Figure 2-48 shows how the onshore gradient winds and coastal topography affect the land/sea breeze circulation. Onshore gradient flow accelerates orographic lifting by day and enhances cloudiness over ridge tops. It also produces localized cloudiness over the open water during the early morning, due to convergence with the land breeze and downslope flow from the high terrain. Coastal configuration also has an effect on land/sea breezes. Coasts perpendicular to landward synoptic flow maximize sea breeze penetration, while coastlines parallel to flow minimize them.

Land/Lake Breezes. Several variations of a land/sea breeze circulation are caused by differential heating over large lakes. This circulation occurs in the absence of strong synoptic flow and has a vertical depth of 600-1,600 feet AGL. Figure 2-49 shows an idealized land/

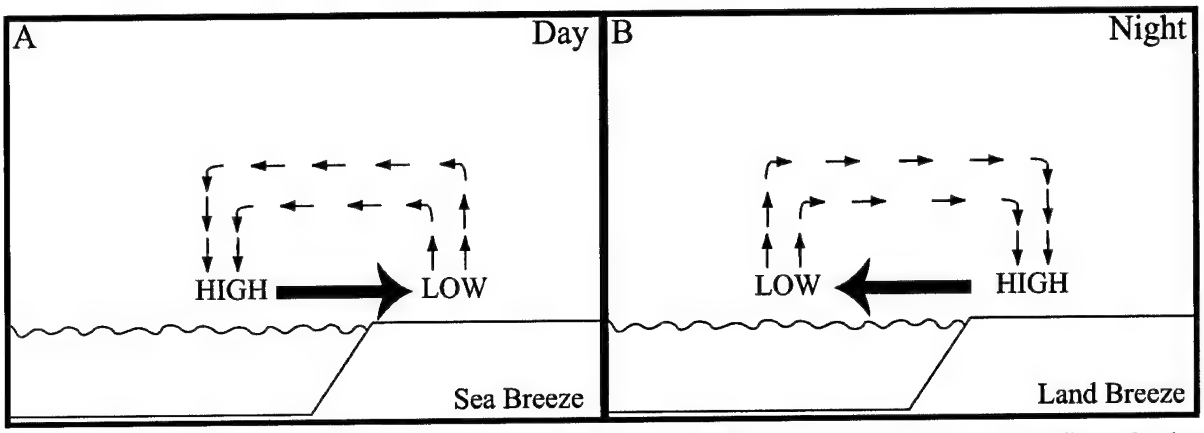


Figure 2-46. The "Common" Sea (A) and Land (B) Breezes. Thick arrows depict the surface flow. Onshore (A) and offshore (B) flow intensifies in proportion to the daily heat exchange between land and water.

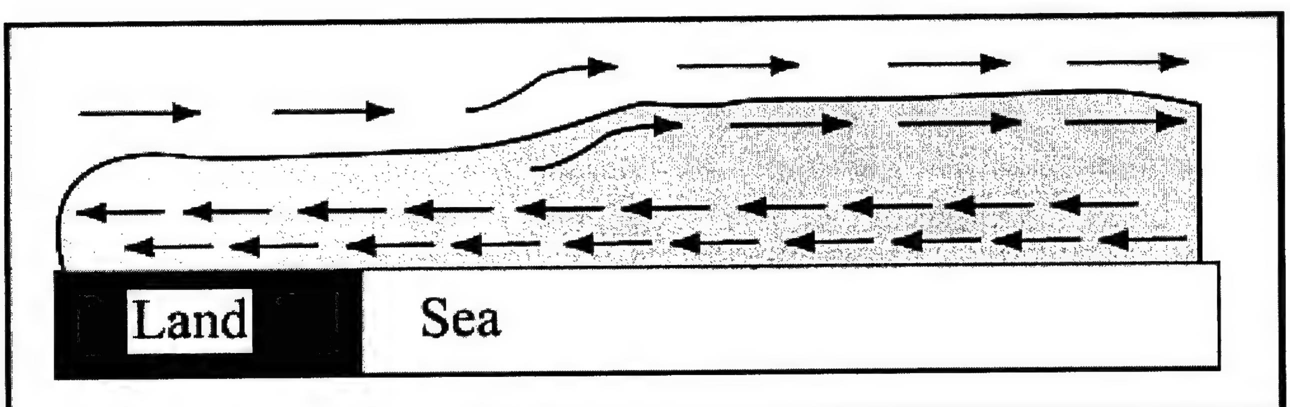


Figure 2-47. A Fully-Formed "Frontal" Sea Breeze. Light arrows depict wind flow; grey-shaded area is the marine air mass; heavy arrows depict low-level jet. Left boundary represents sea breeze "front" onset point.

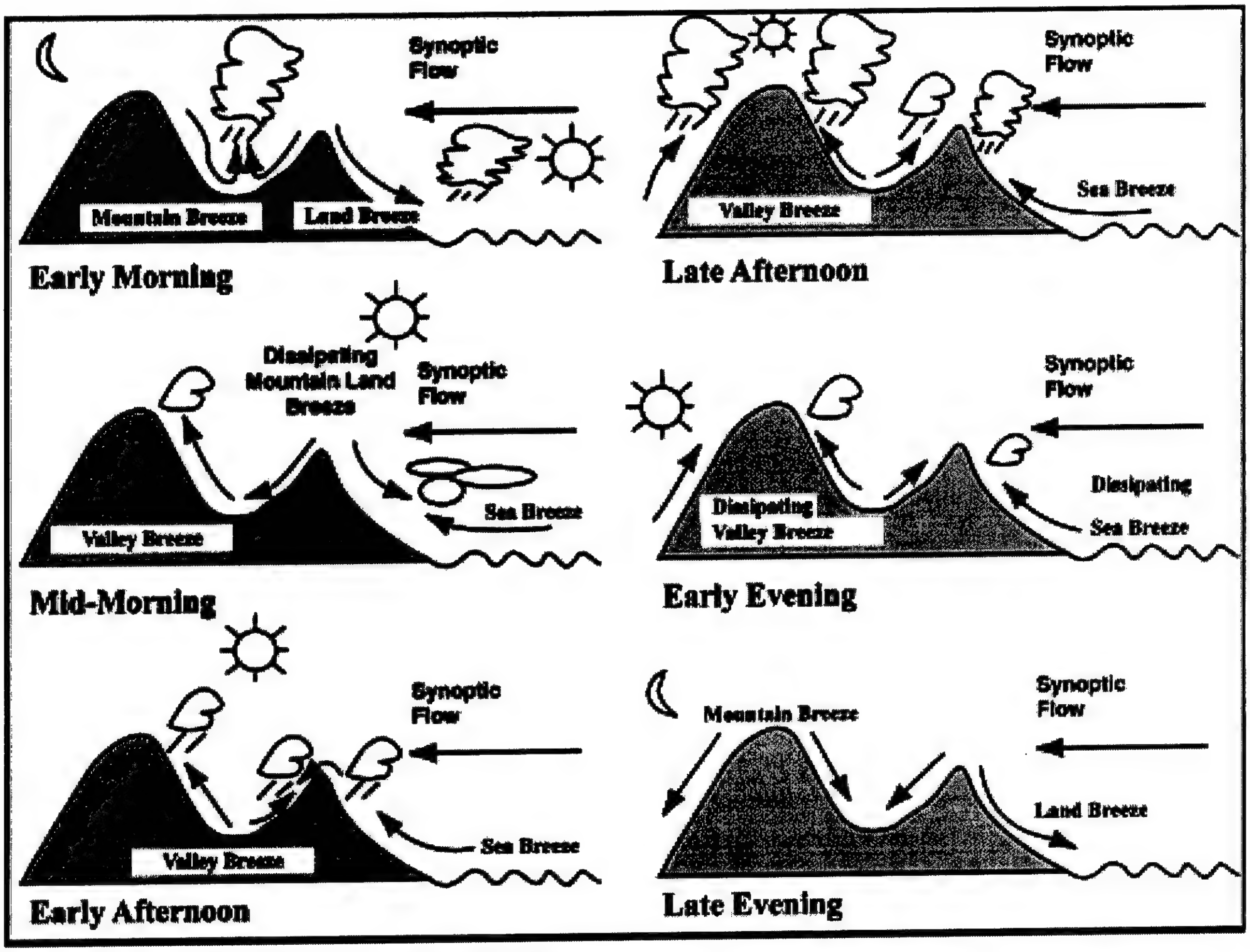


Figure 2-48. Land/Sea Breezes with Onshore Gradient Flow. Topography can lead to localized cloudiness.

lake circulation and its cloud patterns. In the late afternoon (top illustration), a cloud-free lake is surrounded by a 12-24 mile (20-40 km) ring of convection. By early morning, flow reverses and convergence occurs over water.

Mountain/Valley and Slope Winds. These winds develop under fair skies with light and variable synoptic flow. Mountain/valley winds, like land/sea breezes, dominate the weather close to the equator, especially when the monsoon is weak. A strong monsoon diminishes these effects, particularly away from the equator. Nocturnal mountain winds that flow toward the sea are capable of initiating thunderstorm activity, particularly over western Borneo. The two types of terrain-induced winds, valley winds and slope winds, are shown in Figure 2-50 and discussed below. Valley

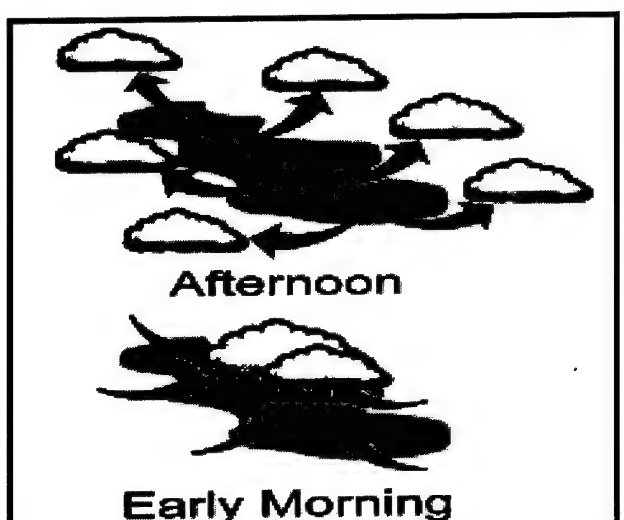


Figure 2-49. Idealized Land/Lake Breezes with Cloud Pattern. Changes in localized convergence leads to changing cloud patterns.

winds tend to be stronger than slope winds and can override their influence.

Mountain and valley winds develop in response to temperature gradients between mountain valleys and nearby mountains. The air on the upper mountain slopes receive sunlight before the valley floor and consequently heats faster. The resulting upslope winds flow during the day and are strongest in the mornings and weaker by afternoon when the temperature is equalized between the mountain slopes and valley floor. The flow reverses at night when the mountain slopes cool faster and cooler air slides downhill.

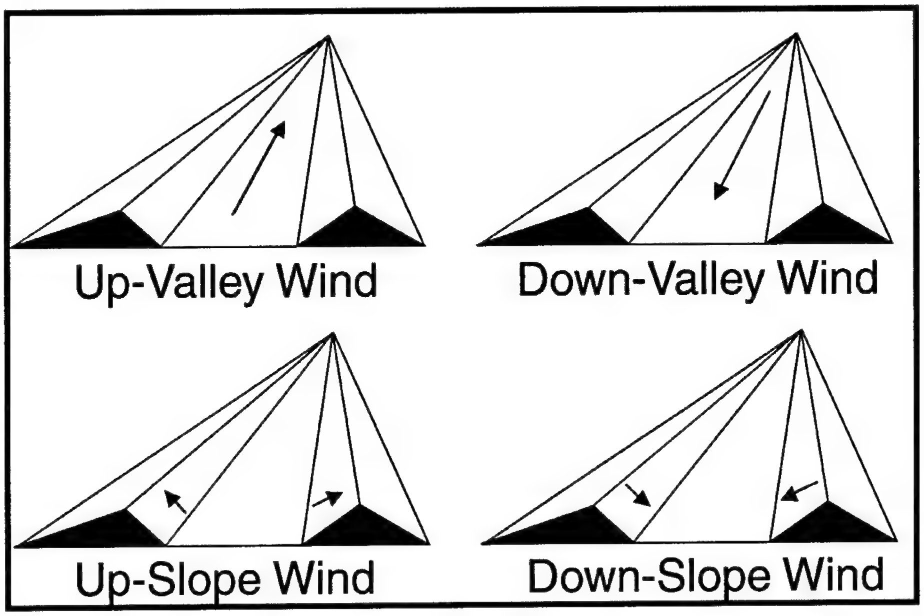


Figure 2-50. Mountain-Valley and Slope Winds. Diurnal temperatures changes trigger these terrain-induced features. The arrows indicate wind flow direction. (Traxler, et al, 1997 from Whiteman, 1990)

The mesoscale mountain-valley circulation has a maximum vertical extent of 6,500 feet AGL. It is determined by valley depth and width, the strength of prevailing winds in the mid-troposphere (stronger winds produce a shallower circulation), and the breadth of microscale slope winds. These winds can spread their influence into nearby plains areas. Upslope winds during the day pull air into the valleys from the plains and night downslope winds send air pooling out over the plains from the valley. Winds exiting onto the plains are called valley winds. This is generally known as a valley/plain circulation.

Slope winds develop in the surface boundary layer (0-500 feet AGL) of mountains and large hills. Mean daytime upslope wind speeds are 6-8 knots; mean nighttime downslope wind speeds are 4-6 knots. Steeper slopes produce higher speeds. Downslope winds are strongest in the winter and upslope winds are strongest during the summer. Upslope winds are also strongest on slopes that face the sun. Winds from a larger mountain can disrupt the winds of smaller mountains. Figure 2-51 shows the life cycle of a typical mountain-valley and slope wind circulation. Both valley and slope winds are shown in relation to two ridges (BK and BB) oriented NNW-SSE. Dark arrows show flow near the ground; light arrows show flow above the ground.

These winds are significant in South Asia. Winds of this nature are generally light, although in the Himalayas, downslope winds may be quite violent at times in constricted portions of a valley. During periods of strong pressure gradients, the channeling effect of the valleys may cause strong winds through the mountain passes and in the valleys.

Mountain Inversions. These develop when cold air builds up along wide valley floors. Cold air descends slopes above the valley at 8-12 knots, but loses momentum when it spreads out over the valley floor. Wind speeds average only 2-4 knots by the time the downslope flows from both slopes converge. The cold air replaces warm, moist valley air at the surface and produces a thin smoke and fog layer near the base of the inversion it creates. First light initiates upslope winds by warming the cold air trapped on the valley floor. Warming of the entire boundary layer begins near the 500-foot AGL level.

Local Wind Systems.

Mountain Waves. These can develop when air is forced over the windward side of a ridge. Criteria for mountain wave formation include sustained winds of at

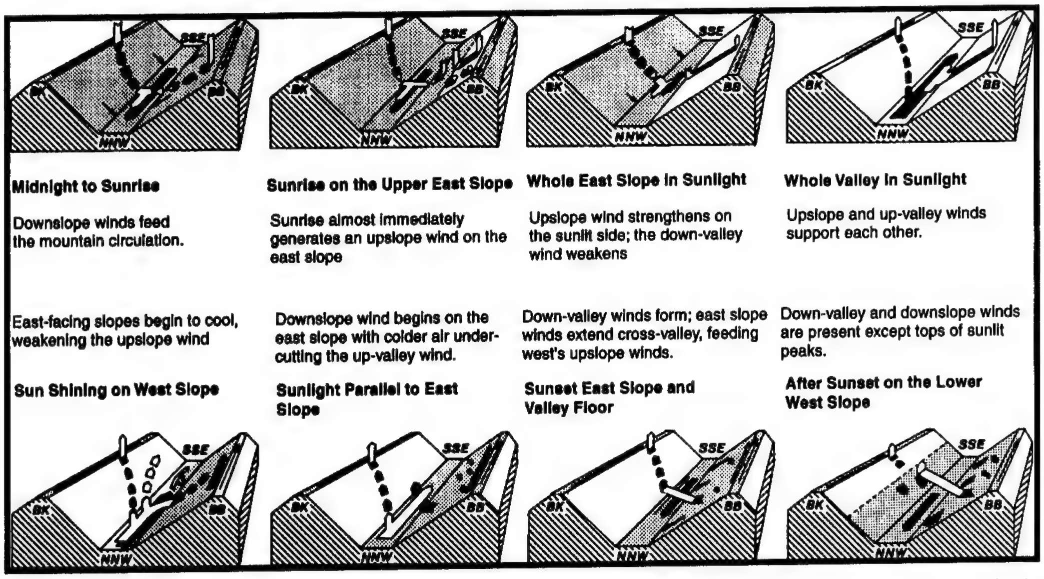


Figure 2-51. Diurnal Variation of Slope and Valley Winds. Both valley and slope winds are shown in relation to two ridges (BK and BB) oriented NNW-SSE. Dark arrows show wind flow near the ground; light arrows show wind flow above the ground. (Traxler, et al, 1997 adapted from Barry, 1991)

least 15-25 knots, winds increase with height, and flow is oriented within 30 degrees of perpendicular to the ridge. The wavelength and amplitude of mountain waves depend on wind speed and the lapse rate above the ridge. Light winds follow the contour of the ridge, with little wave formation. Stronger winds displace air above the stable inversion layer to form waves. This upward displacement of air can reach the tropopause. Downstream, the wave propagates an average distance of 50 times the ridge height. Rotor clouds form when there is a core of strong winds moving over the ridge, but the elevation of the core does not exceed 1.5 times the ridge height. Rotor clouds produce the strongest turbulence. Figure 2-52 shows a fully developed lee wave system.

Foehns. These hot, dry winds occur as air that has been forced over mountain tops descends the leeward slopes adiabatically. Foehn winds are prevalent during the southwest monsoon in Sri Lanka and occur on the lee sides of mountains everywhere. Known locally as kachchan on Sri Lanka, they blow from the central mountains to the east coast. This occurs when the monsoon winds are forced over the mountains and find paths around the mountains. The rising air deposits some of its moisture on the windward slopes and comes down on the other side of the mountain as a hot, dry wind. This wind is usually strong enough to overcome the sea breeze along the east coast.

Jet-Effect Winds. These occur on the downward sides of narrow mountain passes under strong gradient conditions induced by the funneling of the wind. These winds are almost always "supergradient," with speeds as much as 35 to 45 knots higher than prevailing flow. The long, narrow valleys and mountain gaps in the Himalayas are prime locations.

Topographical Influences.

The major mountains in the north and in peninsular India have a marked influence on the climate of the region. The towering Himalayas prevent the intrusion of cold

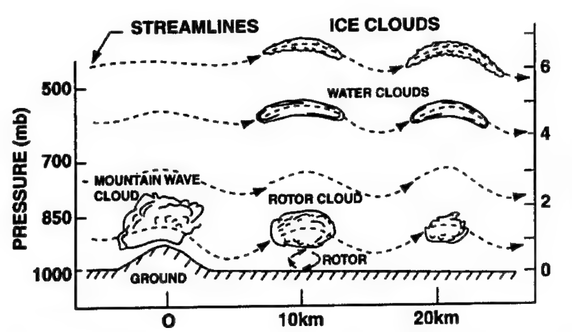


Figure 2-52. Fully Developed Lee Wave System. The figure depicts the features associated with mountain waves including the hazardous rotor cloud located downstream from the wave. (Traxler, et al, 1997 from Wallace and Hobbs, 1977)

air from central Asia. The mountains of western Pakistan also shut out much of the cold air. The most profound effect is in the rainfall distribution. The heaviest concentrations are located on the windward side of the mountains and hills, particularly the Himalayas, the Western Ghats, and the Khasi Hills. During the southwest monsoon, the Himalayas force the moisture-laden winds to deposit most of the moisture on the southern slopes. The Himalayas also increase the rainfall in the plains immediately south of the foothills. The area along and just to the south of the Himalayas usually receives 30-60 inches (762-1,524 mm) of rain between June and September.

The Western Ghats, along the southwest coast of India, take the brunt of the southwest monsoon. Orographic lifting of monsoonal flow results in most of the moisture falling on the western slopes. Many sites along the southwestern coast of India have 100 inches (2,540 mm) or more of rain during the southwest monsoon. The area immediately east of the Western Ghats receives relatively light rainfall, even at the height of the southwest monsoon. Typical rainfall amounts in this area are 12-20 inches (305-508 mm).

The southern slopes of the Khasi Hills in northeastern India, are home to the heaviest rainfall amounts recorded. These hills are the first significant terrain features the moist air from the Bay of Bengal contacts. The orographic lifting inundates the southern slopes with heavy precipitation. Most of it falls between March and October, when the southern wind flow is most persistent. Cherrapunji, on a south slope in the Khasi Hills, has nearly 450 inches (11,430 mm) of rain annually because it is at the top of a unique, funnel-shaped valley that faces the Bay of Bengal. Cherrapungi also holds the world record for the greatest monthly rainfall total (366 inches/9,296 mm) and the greatest 12-month rainfall total (1,041.8 inches/26,462 mm). Like the Western Ghats, the valley just to the north of the Khasi Hills sees significantly less rainfall. Amounts are 1/10-1/8 of those on the windward slopes.

Wet-Bulb Globe Temperature (WBGT) Heat Stress Index. The WBGT heat stress index provides values that can be used to quantify the effects of heat stress on individuals. The WBGT is computed using the formula:

$$WBGT = 0.7WB + 0.2BG + 0.1DB,$$

where: WB = wet-bulb temperature
BG = Vernon black-globe temperature
DB = dry-bulb temperature

A complete description of the WBGT heat stress index and the apparatus used to derive it is given in Appendix A of TB MED 507, Prevention, Treatment and Control of Heat Injury, July 1980, published by the Army, Navy and Air Force. The physical activity guidelines shown in Table 2-4 are based on those used by the three services. The physical activity guidelines shown are based on those used by the three services. Wearing body armor or NBC gear adds 6°C to the WBGT, and activity shoud be adjusted accordingly. Figures 2-53a-c gives the average maximum WGBTs for each month of the year. For more information, see *USAFETAC/TN-90/005, Wet Bulb Globe Temperature, A Global Climatology.*

Table 2-4. WBGT Heat Stress Index Activity Guidelines.

WBGT (°C)	Water Requirement	Work/Rest Interval	Activity Restrictions
32+	2 quarts/hour	20 min/40 min	Suspend all strenuous exercise.
31-32	1.5 quarts/hour	30 min/30 min	No heavy exercise for troops with less than 12 weeks hot weather training.
29-31	1.0-1.5 quarts/hour	45 min/15 min	No heavy exercise for unacclimated troops, no classes in sun, continuous moderate training third week.
28-29	0.5-1.0 quart/hour	50 min/10 min	Use discretion in planning heavy exercise for unacclimated personnel.
24-28	0.5 quart/hour	50 min/10 min	Caution: Extremely intense exertion may cause heat injury.

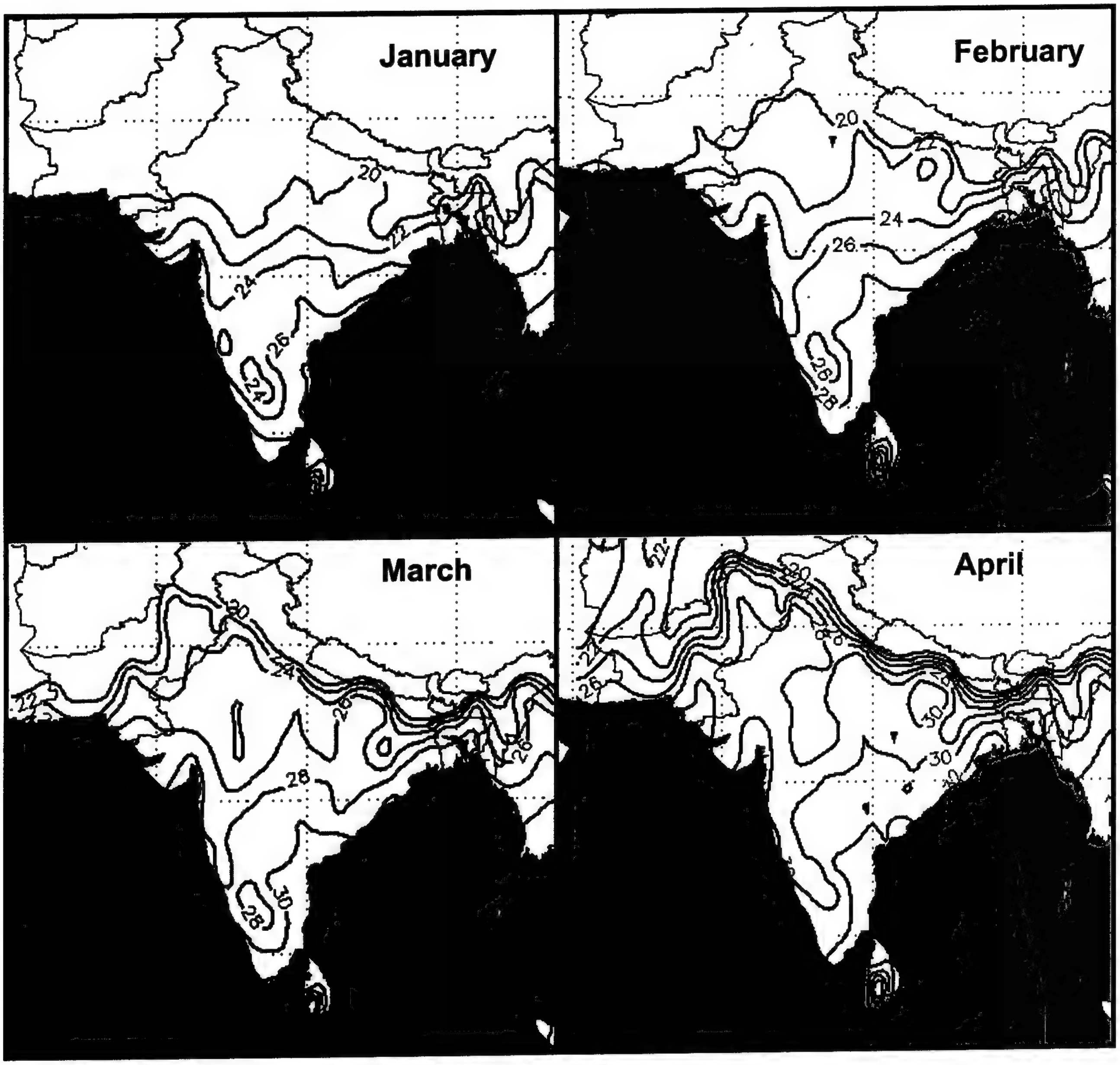


Figure 2-53a. Mean Maximum Wet-Bulb Globe Temperatures (January-April).

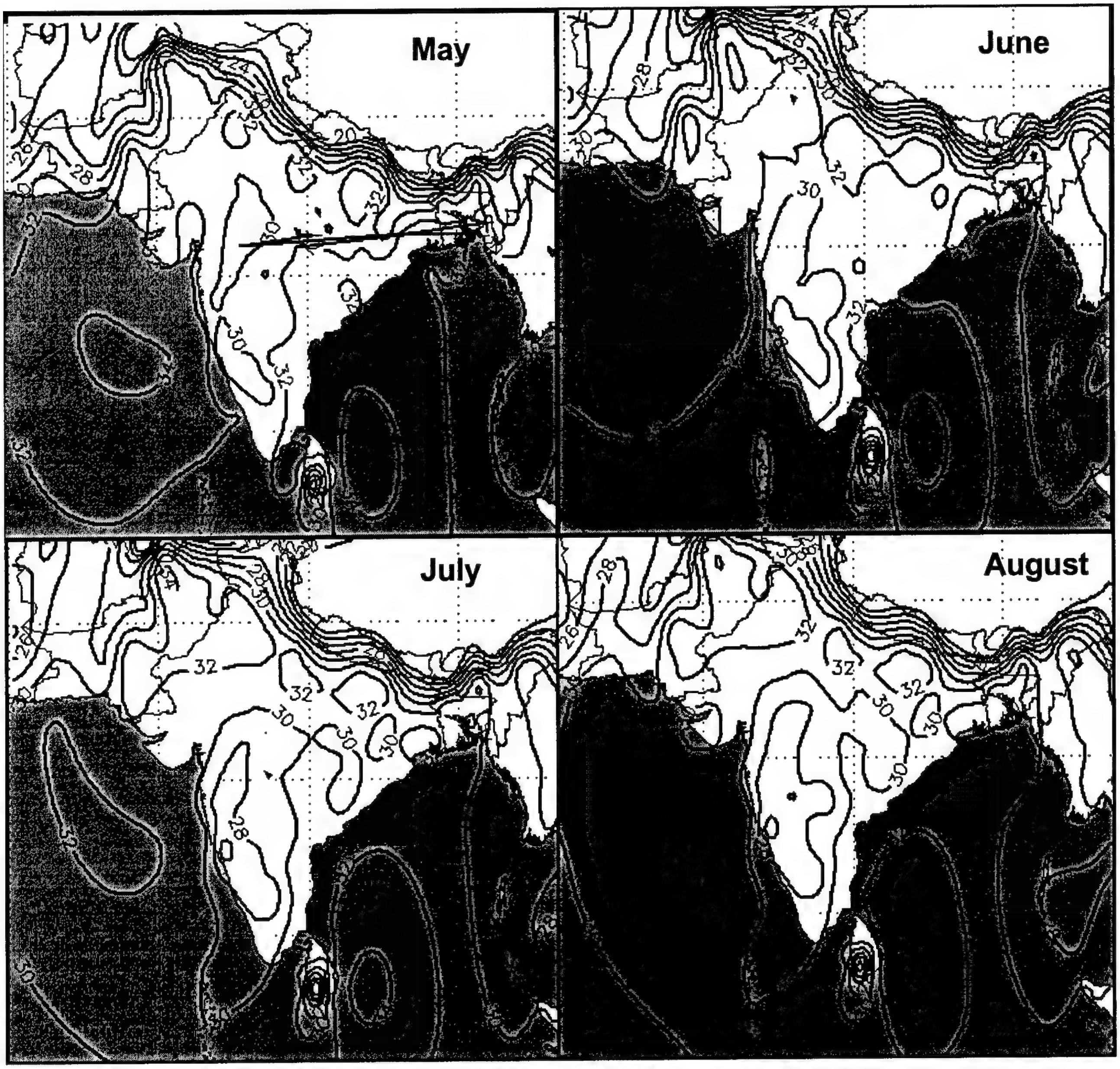


Figure 2-53b. Mean Maximum Wet-Bulb Globe Temperatures (May-August)

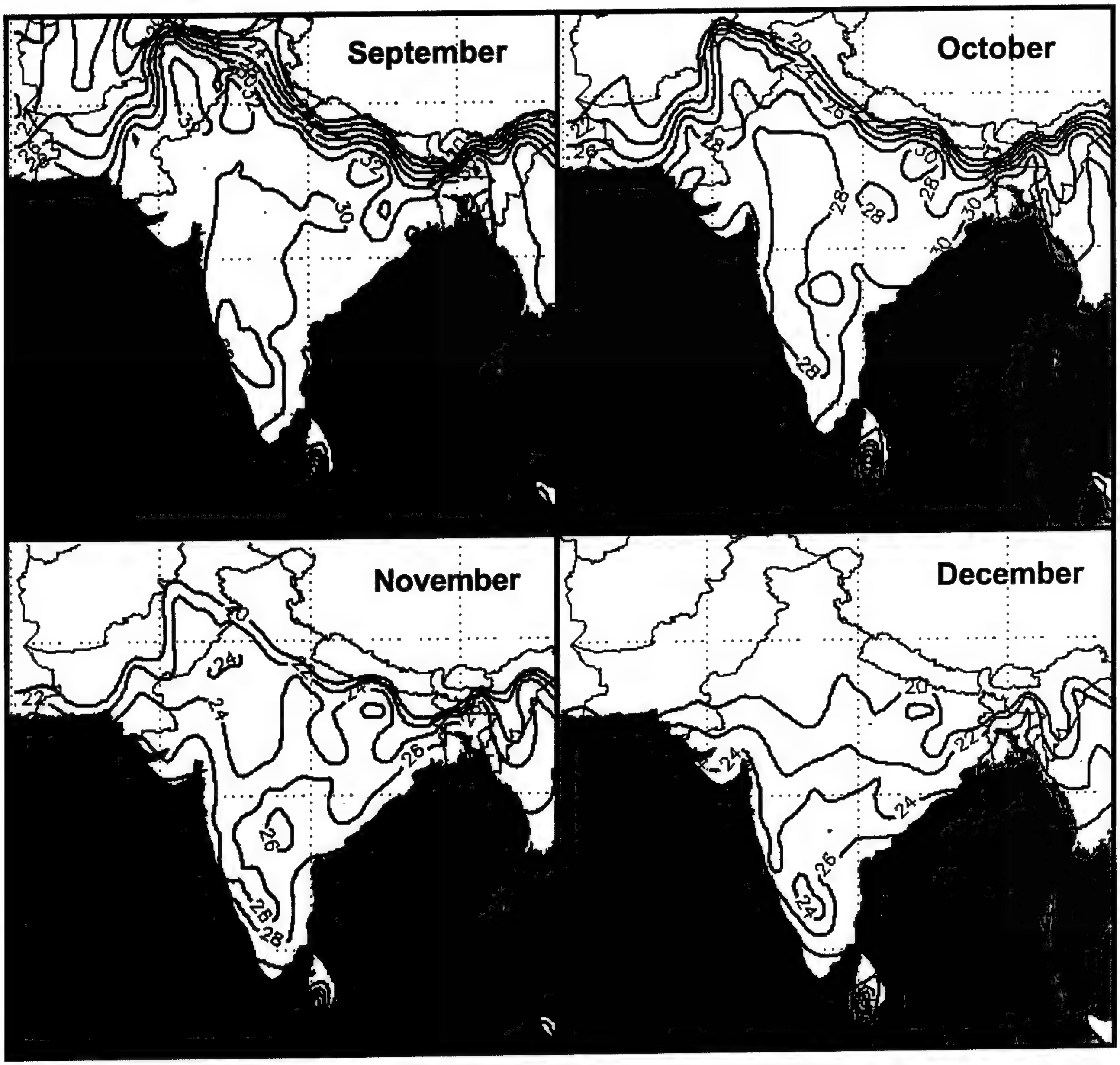


Figure 2-53c. Mean Maximum Wet-Bulb Globe Temperatures (September-December).

Chapter 3

BANGLADESH AND NORTHEAST INDIA

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for Bangladesh and Northeast India.

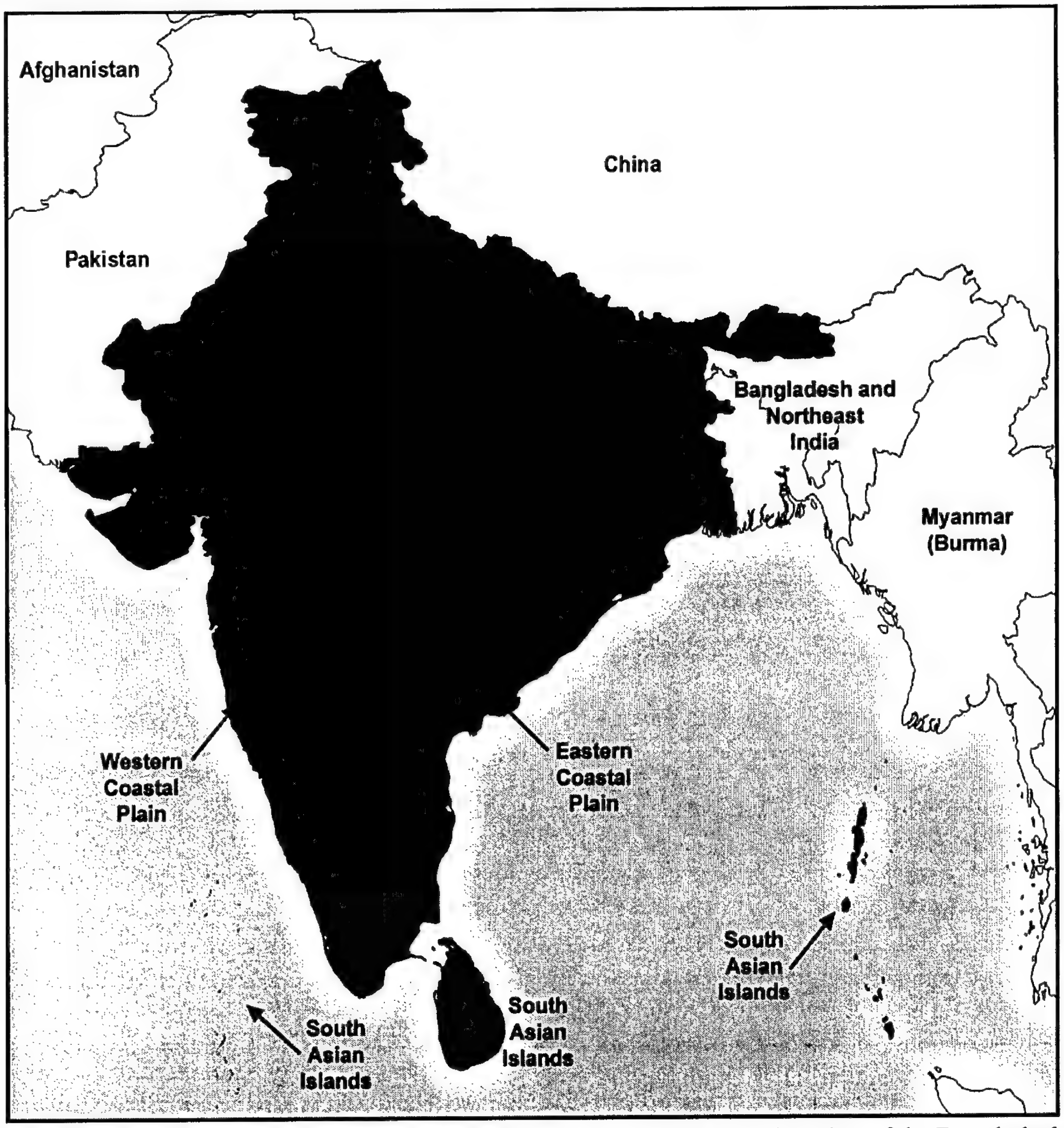


Figure 3-1. Bangladesh and Northeast India. This figure shows the location of the Bangladesh and Northeast India (highlighted in yellow) in relation to the other zones.

List of Topics

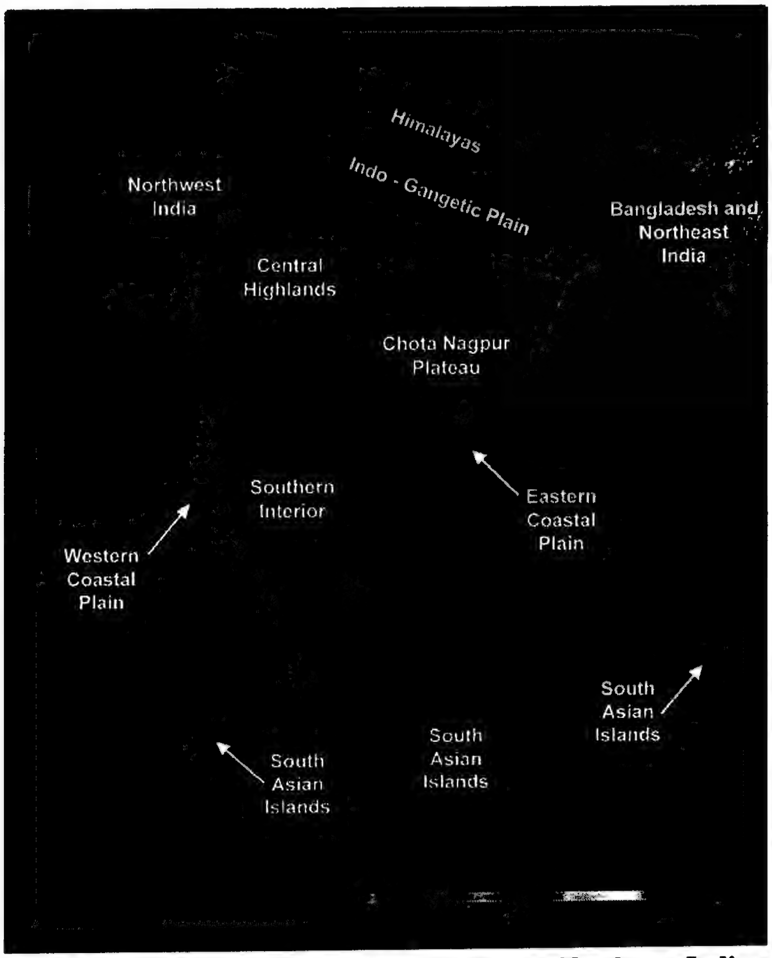


Figure 3-2a. Topography of Bangladesh and Northeast India

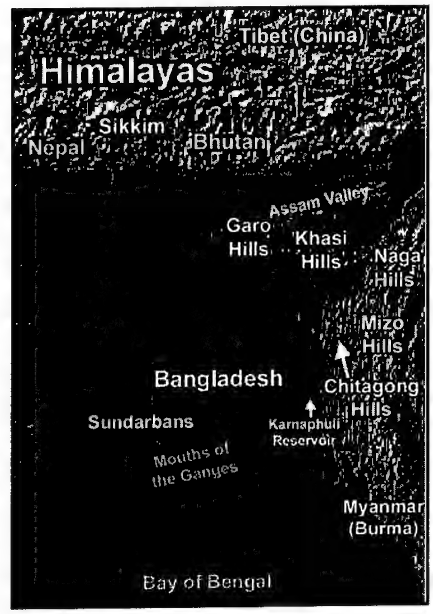


Figure 3-2b. Expanded View of the Topography of Bangladesh and North-east India

Topography

Bangladesh. This country consists of two basic terrain types. The majority is a vast river delta that handles the Brahmaputra and Ganges River systems. This area is part of the great Bengal basin. The two large rivers have many sub-channels and tributaries all through Bangladesh. All ultimately empty into the Bay of Bengal through the Sundarbans, a low-lying, marshy area of multiple river mouths (Mouths of the Ganges) and sediment. This fertile lowland is collectively called the Bangladesh Plain or the Lower Gangetic Plain. Higher elevations include the Chittagong Hills in the southeast, hills in the northeast, and highlands on the north and northwest rim of the country.

Mountains. The Chittagong Hills, in southeast Bangladesh, are the western fringe of the north-south oriented mountains of Myanmar and Northeast India. A series of narrow blade ridges, they average only 120 feet wide at the top and rise 2,000-3,000 feet. The hills in the northeast corner of Bangladesh are the southern foothills of the Khasi Hills and Garo Hills, which are mostly in East India. The hills are oriented generally east-west and rise 3,000-5,500 feet. A few peaks are as high as 6,400 feet. In the far north-northwest corner of Bangladesh, the foothills of the Himalayas begin to rise. The mountains themselves are north of the country. Like the Himalayas, the hills are oriented generally east-west. Average elevation for the hills is 300-500 feet in an area where most of the land is at 150-200 feet.

Major Water Bodies. Aside from the many rivers, the only body of water is the Bay of Bengal. Although not in direct contact with Bangladesh, the Indian Ocean provides significant moisture during the southwest monsoon season.

Rivers. Approximately 700 rivers in Bangladesh drain the massive rainfall of the highlands. The Jamuna-Brahmaputra extends from northern Bangladesh to its confluence with the Padma. The Padma-Ganges extends from the western border of Bangladesh and is the central figure in the vast deltaic river system. Both systems have hundreds of rivers and streams that merge into them. The Surma-Meghna flows from the northeast border to a confluence with the Padma. Six major tributaries join this river before it merges with the Padma. This conjoined river then becomes the fourth major river system, the Padma-Meghna, which flows to the Bay of Bengal 90 miles (145 km) away. These 4 river systems all empty into the Bay of Bengal through the great Bengal basin (also known as the Gangetic basin) via the massive delta area known as the Mouths of the Ganges or the Sundarbans. A fifth major system, unconnected to the others, is the Karnaphuli. It flows through the Chittagong Hills and races rapidly west, then southwest to the sea (at the city of Chittagong). An aggregate of several rivers feeds into the Karnaphuli.

Lakes. Karnaphuli Reservoir is a large, man-made lake fed by the Karnaphuli River. It lies northeast of the city of Chittagong and fills the valleys on either side of a 1,000-foot high, narrow ridge. There are thousands of small lakes in Bangladesh, but the land is dominated by the rivers that drain the mountains.

Northeast India. This region is a mix of mountains and valleys. Listed in a progression from south to north, the Mizo Hills, Manipur Hills, Jaintia Hills, Naga Hills, Patkai Hills are the main feature of the eastern half of the area. The Khasi Hills and the Garo Hills (along the shared border with Bangladesh) cover much of western East India. In the northwestern corner of East India (along the borders of Bhutan, China, and Nepal), the Himalayas dominate. The narrow strip of land between Nepal and Bangladesh that connects East India to the rest of India is a northern alluvial plain at the foot of the Himalayas. Assam Valley separates the Himalayas and the hills of both the west and the east. The huge Brahmaputra River flows down this valley from the northeastern corner of the region into Bangladesh around the western end of the Garo Hills. West of the Mizo Hills, in the south end of East India, a small area of East India is part of the great Bengal basin, which is largely in Bangladesh. This area includes the low foothills on the western edge of the eastern ranges.

Mountains. The Mizo Hills, Manipur Hills, Jaintia Hills, Naga Hills, Patkai Hills are all oriented more or less north-south. The Mizo Hills are mainly sharp, narrow ridges an average of 120 feet (36 meters) across at the top. They range 2,500-3,500 feet (750-1,000 meters) on the west side and progressively rise to 6,000-7,000 feet (1,800-2,100 meters) at the Myanmar (Burma) border. The Manipur Hills and Naga Hills are also series of ridges but not as sharp as the Mizo Hills. The average elevation is higher as well, an average of 8,000-9,000 feet (2,400-2,700 meters). The Jaintia Hills, between the Manipur Hills and the Khasi Hills, are lower and less clearly ridged. They average 4,000-6,000 feet (1,200-1,800 meters) and connect the two mountain ranges. The Khasi Hills and the Garo Hills are oriented east-west, like the Himalayas in the north part of the country. These are a series of high hills that average 4,500-6,000 feet (1,400-1,800 meters). Numerous rivers lace through these high hills in every direction. Cherrapunji, world record holder for rainfall, is in the south-central Khasi Hills. In the north, the Himalayas dominate. The mountains quickly rise from 200-300 feet (60-100 meters) at the valley floors to 16,000 feet (4,800 meters) and higher at the northern East Indian borders. This vast massif gives rise to almost all the rivers of India.

Major Water Bodies. The Bay of Bengal is the main body of water for East India. The Indian Ocean also plays an important role in the weather in this country. It provides a significant part of the moisture in the air during the southwest monsoon season.

Rivers and Lakes. The Brahmaputra is the major river system in East India. It flows through Assam Valley, around the west end of the Garo Hills, and into Bangladesh where it joins the Jamuna River. It flows from the Himalayas in the northeast corner of the country and has many tributaries. Although there are many lakes, they are all small. Loktak Lake, in the Manipur Hills just south of Imphal, is a seasonal feature. The Manipur River fills it in the southwest monsoon, but most of it dries up during the northeast monsoon. When it does exist, it is the largest lake in East India and takes up the southern end of the Imphal valley. When it dries up, it leaves behind an extensive marshy area.

Major Climatic Controls

Asiatic (or Siberian) High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. The vast pool of cold, dry air it pushes outward in all directions is a key part of the northeast monsoon in south Asia. Because of the continental source of the air, the weather is dry. The lee-side trough on the southern side of the Himalayas created by flow out of this high provides a track for storms that move out of Europe on the subtropical jet.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough, intertropical convergence zone (ITCZ) or near-equatorial trough (NET) in this region, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north, the southwest monsoon takes over in South Asia. When it shifts south, the northeast monsoon assumes control. Chapter 2 offers more details.

Australian High. This thermal high sets up over Australia during Southern Hemispheric winter. It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the ET northward to produce the southwest monsoon season.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon. This high, which forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area, influences the tracks of low-pressure systems depending on its strength and position. Although typically weak, when the high is at its strongest, it tends to block low pressure systems from the track across the southern foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe that ride the subtropical jet to move rapidly across northern India.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in the Northern Hemisphere summer and east and south in the winter. The high is linked to the position of the ET.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south with the sun. At its strongest during the Southern Hemisphere winter, it provides cross-equatorial flow from May to October. This warm, moist flow contributes to the ET shift to the north.

Asiatic Low. This is a thermal low that replaces the Asiatic high during the Northern Hemisphere summer. The land heats, and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This thermal low develops over Australia during the Southern Hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the area of the Bay of Bengal and is a southwest monsoon feature. Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has a distinct rainy season and dry season. Under the northeast monsoon, the region is largely dry. Under the southwest monsoon, it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid-May and late June. In the north, the southwest monsoon season is short. On the southern end of the peninsula, it lasts longer, often twice as long as in the far north.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclones. Most of the rainfall in this area occurs from storms that develop or refire over this body of water along the ET, the India-Myanmar trough,

or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season (May through October). An upper level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the east African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It has been suggested 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa (May through October). The western edge of the outflow air mass piles up against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the northern hemisphere. The air mass is recurved eastward and these westerly winds take over throughout the monsoon region.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season (November to April) when its southern branch slips south of the Himalayas. Low pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. During the southwest monsoon, the STJ is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter (November through April), several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move these waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere (southwest monsoon) upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere mid-latitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For a more detailed description, review chapter two.

Easterlies. This deep east wind band persists year round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season (May through October), easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off shore the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over Sri Lanka and the southern tip of the peninsula. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are all types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). Some of these factors have influence during the southwest monsoon season, such as the Tibetan anticyclone, easterly waves and the India-Myanmar trough. The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the bay are so confined, however, storms do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET (monsoon trough) toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the large scale flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Off shore winds clear the skies over land by pushing the cloud cover out to sea. These same winds can slide convection that developed over the mountains down into the lowlands between them and the sea. Depending on the steepness of the slopes, the downslope flow can create a "front" that fires thunderstorm activity all along the convergence zone between the cool mountain air and the warmer, moist air of the sea. This makes up a line of thunderstorms that marches to the sea over the lowlands.

Nor'westers. These are thunderstorms that occur in the winter and hot seasons, the most in the hot season. They form in the Bengal basin (the greater Ganges River basin) and frequently develop in the same place at the same time of day several days in a row. These thunderstorms can be extremely violent. They produce high wind gusts, hail, and occasional tornadoes. They develop in the convergence zone between cooler, drier air that flows from the east out of the Brahmaputra River valley around the Khasi hills and the warmer, moister air from the Bay of Bengal. Once they fire, they spread westward along the convergence point between the two air masses.

Northeast Monsoon Hazards. The mean freezing level is 13,000-15,000 feet in this season and there is little cloud cover, so icing is not a significant hazard. Turbulence occurs mostly with fronts associated with migratory lows. Over irregular terrain, such as mountains, thermals cause light to moderate turbulence up to 10,000 feet in the afternoons. Low-level easterly winds from Brahmaputra River valley flow into the Ganges Plain. Westerlies overlay this surface flow and turbulence occurs in the Ganges Plain where the two meet. Nor'westers, in the same area, can become severe enough to produce tornadoes and hail. Although the typhoon season officially ends in November, typhoons have occurred in every month of the year. They bring high winds, huge storm surges, and heavy downpours wherever they make landfall. Amount of damage varies with storm intensity. Nor'westers, violent thunderstorms, occur in February in the Bengal basin between the Khasi Hills and Eastern Ghats. They produce hail, high winds, and tornadoes.

Hot Season Hazards. The mean freezing level is 15,000-18,000 feet in this season , and there is little cloud cover, so icing is not a significant hazard. Nor'westers occur in the Bengal basin through May and can produce tornadoes and hail.

Southwest Monsoon Hazards. The mean freezing level is 18,000 feet. Multilayered cloud cover can top 35,000 feet. Icing can be expected through the layer between 18,000 feet and 25,000 feet. Turbulence is mostly with cumuliform cloud formation and thunderstorms. Thunderstorms and/or heavy rains occur just about every day. Just the amount of rain that falls is a hazard because of flooding. The typhoon season is officially from June to November. These storms bring high winds, huge storm surges, and heavy downpours wherever they make landfall. Amount of damage varies with storm intensity.

Post-Monsoon Hazards. The mean freezing level is 16,000 feet. In the north, cloud cover is diminishing so icing is not a significant hazard. In the central and southern areas, multilayered cloud cover can top 35,000 feet. Icing can be expected between 16,000 feet and 25,000 feet. Most turbulence in early October is related to cumuliform cloud development and thunderstorm activity. By late October, mechanical turbulence is the main type. Flooding occurs with heavy rains in south and central areas as November is the rainiest month of the year in those areas. The threat is severely reduced in the north parts of the area by the end of October. Peak typhoon season is October and November.

Winter

General Weather. In winter, the northeast monsoon dominates. The Asiatic high is the driving force for moving the equatorial trough (ET) south of the equator. The Australian low helps pull it southward. This is a dry season influenced by migratory lows from Europe. The STJ shifts south of the Himalayas and pushes lows along the lee-side trough at the southern foot of the mountains. The moisture retained after the long trip from Europe is joined by a little moisture from first the Arabian Sea, then the Bay of Bengal as the lows zip through the northern section of India, Bangladesh, and east India. These migratory lows keep India cooler and more cloudy than would be expected for mostly offshore air flow. The deep band of easterlies that dominate upper-air flow in the southwest monsoon is held south of 5° N and does not influence the weather in this region nearly as much as the westerlies that take over in this season.

Onset of the northeast monsoon, or winter, season depends on latitude and terrain. The ET retreat southward marks the onset on the season. It occurs first in the north and last in the south end of the region. Usually, the ET has moved south of the north part of the region by the first of October and is out of the area completely by the end of the month.

Western disturbances occur mostly in winter and the hot season (November to April). They follow the lee-side trough at the southern foot of the Himalayas and are driven by the STJ. They move from west to east and give rise to cloudiness and precipitation. Nor'westers, storms that can produce severe thunderstorms, tornadoes, and hail in and near the Ganges Plain also occur in this season. While Nor'westers are more common in the hot season, they have occurred in February. These storms often recur in the same place at the same time several days in a row, mostly in the afternoon. They occur from the west end of the Khasi hills to the Eastern Ghats.

Tropical cyclones and other cyclonic storms are less likely in this season than during the southwest monsoon, but there is an incidence of at least one storm in every month of the year. The minimum number occurs in February, when the northeast monsoon is at its greatest strength.

Sky Cover. Winter cloudiness is predominantly middle and high cloud types with bases above 9,000 feet. There is little diurnal variation in cloud cover on the coast, but cumulus forms in the afternoons inland and dissipates after sunset. In the early mornings, particularly over river valleys, low stratus may develop from lifting fog but quickly dissipates soon after sunrise.

Ceilings below 5,000 feet occur progressively less in most places from a maximum in December to a minimum in February. Most places have morning ceilings below 5,000 feet less than 10 percent of the time in December and less than 5 percent of the time in January and February. In the afternoon, ceilings below 5,000 feet are uncommon. Imphal, in a marshy valley in the eastern mountains, has them 40 percent of the time in December, then 20 percent of the time in January and February. The ceilings are caused by upslope flow from the valley floor to the mountain slopes. Cloud bases develop at the lifting condensation level (LCL). Once the sun reaches the valley floor, cloud cover dissipates. By afternoon, these typically broken ceilings occur less than 5 percent of the time the rest of the day. Sibsagar, in the Brahmaputra River valley close to the Khasi Hills (against the windward slopes), has ceilings below 5,000 feet 70 percent of the mornings and 35-45 percent of the time the rest of the day. Places in the mountains have a higher incidence of afternoon ceilings than those at lower elevations. Shillong, in the eastern Khasi Hills, has ceilings below 5,000 feet 65-70 percent of the afternoons in December and January and 45 percent of the afternoons in February. The rest of the day, it gets them only 10-20 percent of the time. Figure 3-3 shows regional ceilings below 5,000 feet in January.

In most places, ceilings below 1,000 feet occur very rarely. Sibsagar is an exception. It gets them 45-55 percent of the mornings in low stratus from lifting fog and those ceilings remain the rest of the day 15-25 percent of the time with the most in December and the least in February. In the mountains, in places like Shillong, these low ceilings occur 15-20 percent of the afternoons but under 5 percent of the time the rest of the day.

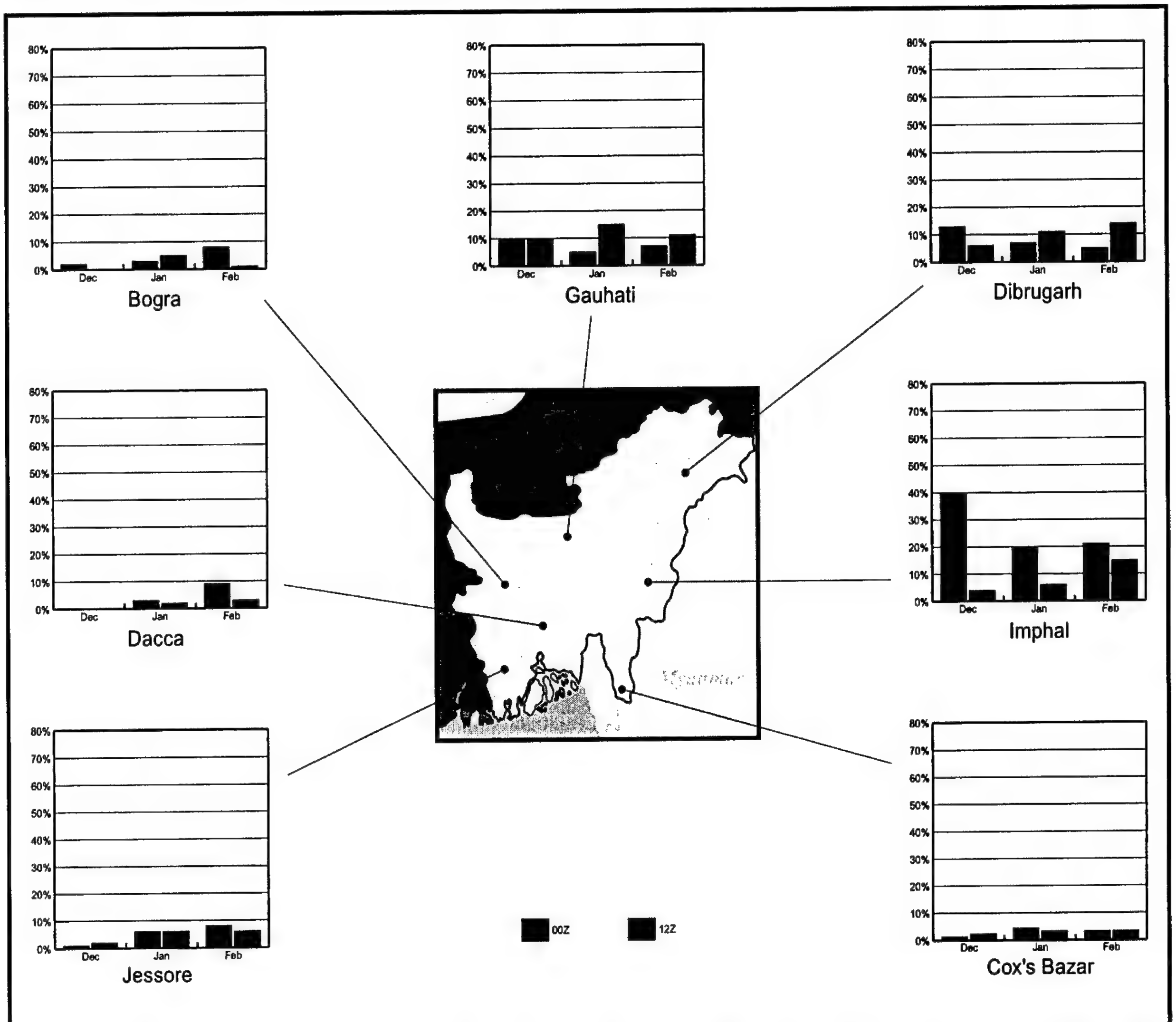


Figure 3-3. Winter Percent Frequency of Ceilings below 5,000 Feet . The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Fog is the most frequent cause of restrictions in winter under clear, calm skies. Valley fogs normally form under shallow inversions, however, under the right conditions, they can be hundreds of feet thick in the Brahmaputra River valley. Land fogs usually form in the early morning and dissipate by mid-morning. In rare conditions, under a stalled migratory high, fog can persist for days with only a slight lessening during the afternoons. Large cities experience the most smog in winter, especially during the early mornings.

In most places, visibility below 2 1/2 miles (4,000 meters) occurs under 5 percent of the mornings and rarely the rest of the day. At higher elevations, visibility restrictions depend on position relative to prevailing winds. Those in windward positions get progressively worse morning visibility from December to February as northeast flow gets stronger. Visibility is below 4,000 meters 10-15 percent of December mornings but 25-30 percent of January and February mornings. By afternoon and for the rest of the day, it occurs under 5 percent of the time in December and under 10 percent of the time in January and February. Visibility below 4,000 meters occurs more on the south (windward) side of the Brahmaputra River valley than on the north side and more in the morning than at any other time of day. Gauhati and Sibsagar, both on the south side of the Brahmaputra River and at the feet of wind-facing hills, get morning visibility below 4,000 meters 60-70 percent of the time. By afternoon, the rate drops to 30-40 percent of the time. In contrast, places in the lee of the Himalayas have morning visibility below 4,000 meters 15-20 percent of the time in the mornings in December and under 10 percent of the time in January and February. By afternoon, the rate drops to well under 5 percent of the time. Figure 3-4 depicts January percent frequency of visibility below 4,000 meters fro various regional locations.

Visibility below 1 1/4 mile (2,000 meters) occurs more on the south (windward) side of the Brahmaputra River valley than on the north side and more in the morning than any other time of day. Most places, especially the lowlands of Bangladesh, rarely see visibility this low. The Brahmaputra River valley on the south side of the river has the worst visibility in the region. There, visibility in morning fog is below 2,000 meters 30-40 percent of the time in December, 40-50 percent of the time in January, and 15-25 percent of the time in February. Fog burns off by mid-morning most of the time, but lingers under strong inversions. Afternoon visibility remains below 2,000 meters up to 15 percent of the time in December and January and up to 10 percent of the time in February. On the other side of the river, under the lee of the Himalayas, visibility below 2,000 meters rarely occurs.

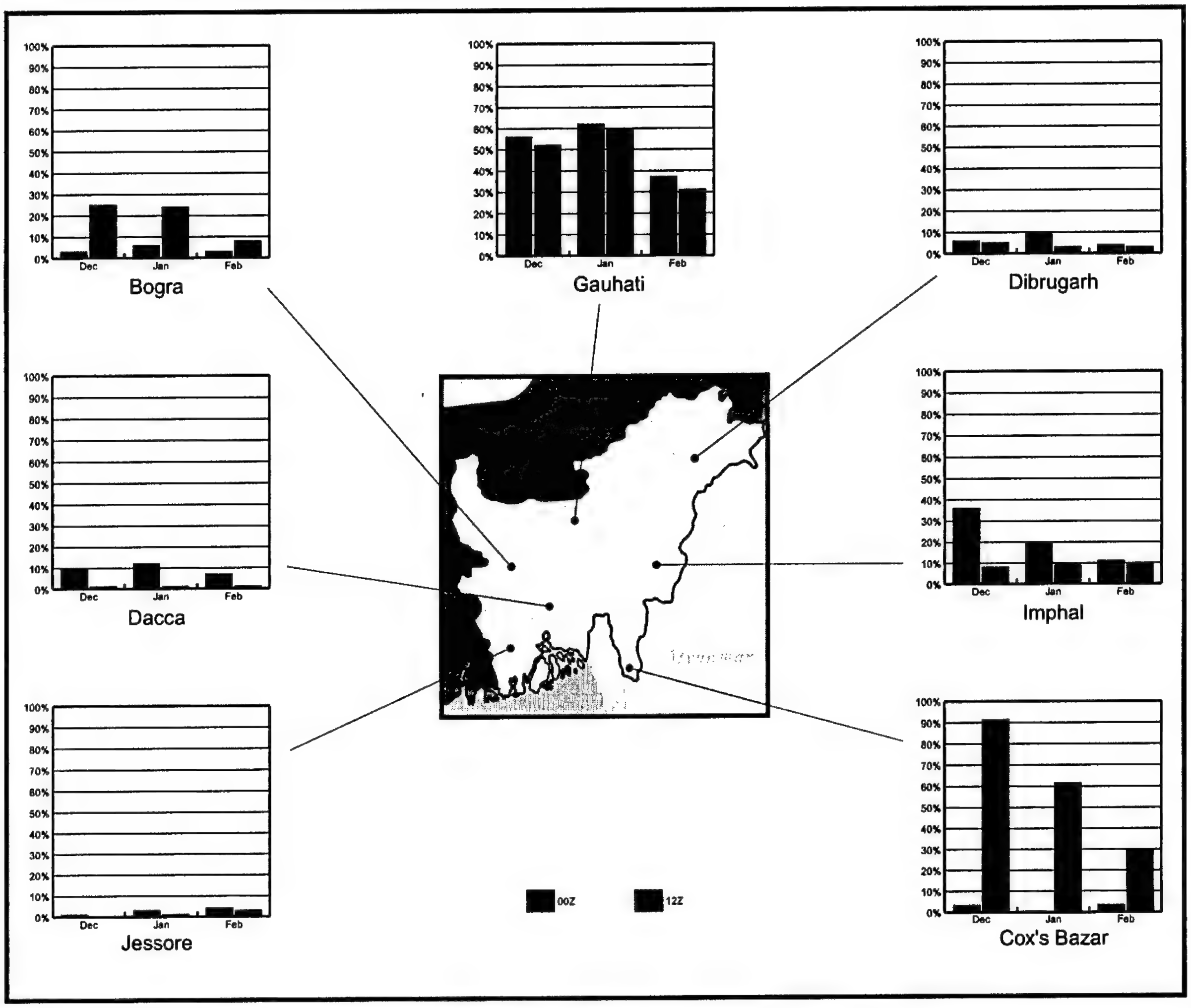


Figure 3-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters) . The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Cooler, drier air flows west-southwestward out of the Brahmaputra River valley as it descends from the Himalayas and allows gravity to guide it around the west end of the Khasi Hills. It is augmented by general northeasterly flow. In the river valley, wind speeds average 5-10 knots but occasionally reach 15-20 knots. In the highlands, overall flow is from the northeast at 5-10 knots, but terrain influences both direction and speed. In the mountains of eastern India, valleys often nearly parallel northeast flow, which reduces the local effect of mountain/valley breezes. In Bangladesh, the land rises so gradually and is so flat, sea breezes reach a long way inland. During the night and morning hours, north or northeast winds dominate Bangladesh at 5 knots. During the afternoon, earliest on the coast, south winds blow at 5-10 knots. The closer to the coast, the stronger the sea breeze. Figure 3-5 shows January surface winds around the region.

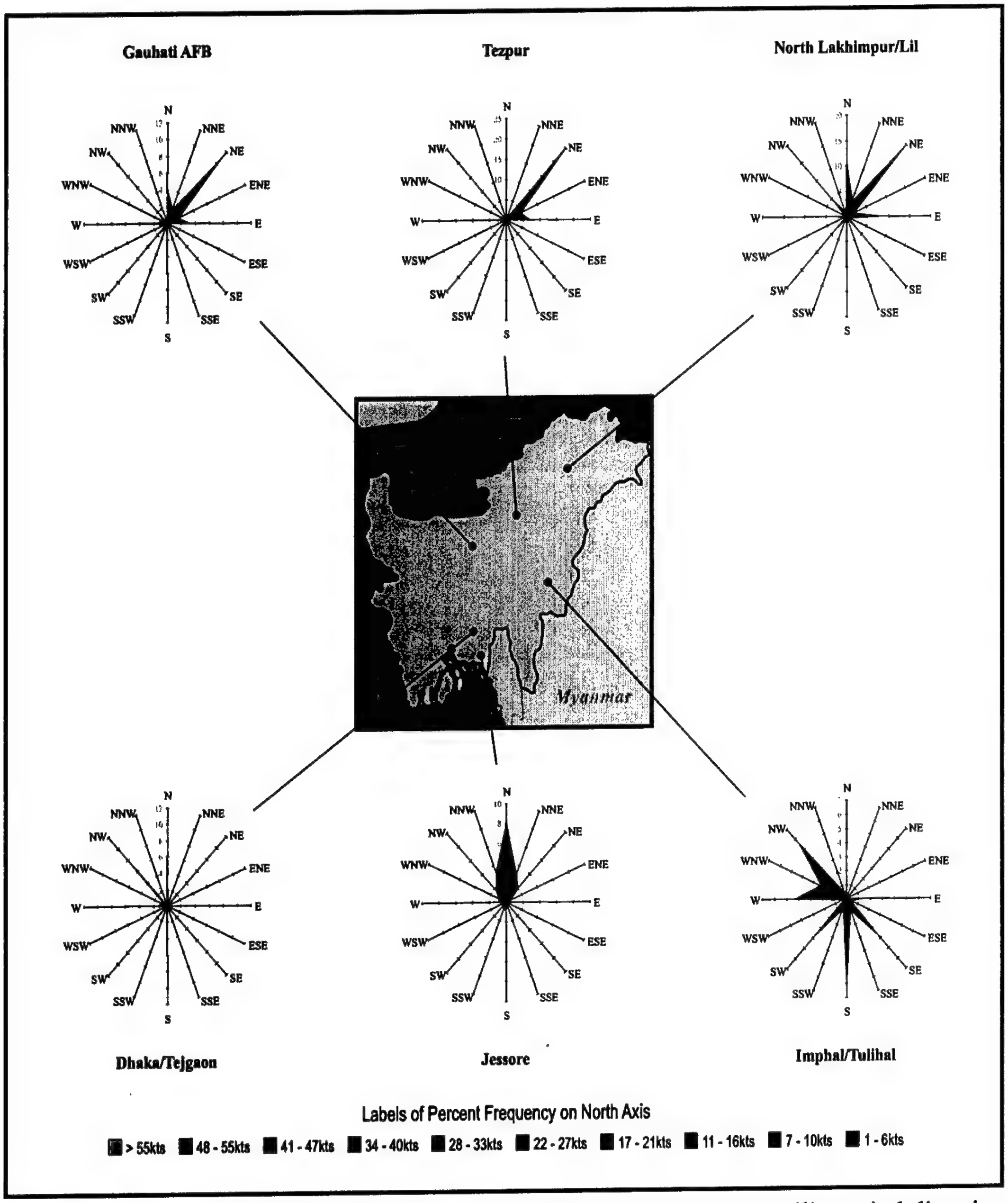


Figure 3-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. December and January 850-mb winds are northwesterly at 10 knots in western Bangladesh and northeasterly at 10 knots in the rest of the region. In February, they are variable at 5 knots. From December through February, the 700-mb winds are westerly at 15-20 knots. At 500 mb, westerly winds at 40 knots dominate the season. Westerlies continue to rule at 300 mb; there they are at 70-75 knots. The subtropical jet averages 95-105 knots at 200 mb. See Figure 3-6 for typical January upper-air winds over Dacca.

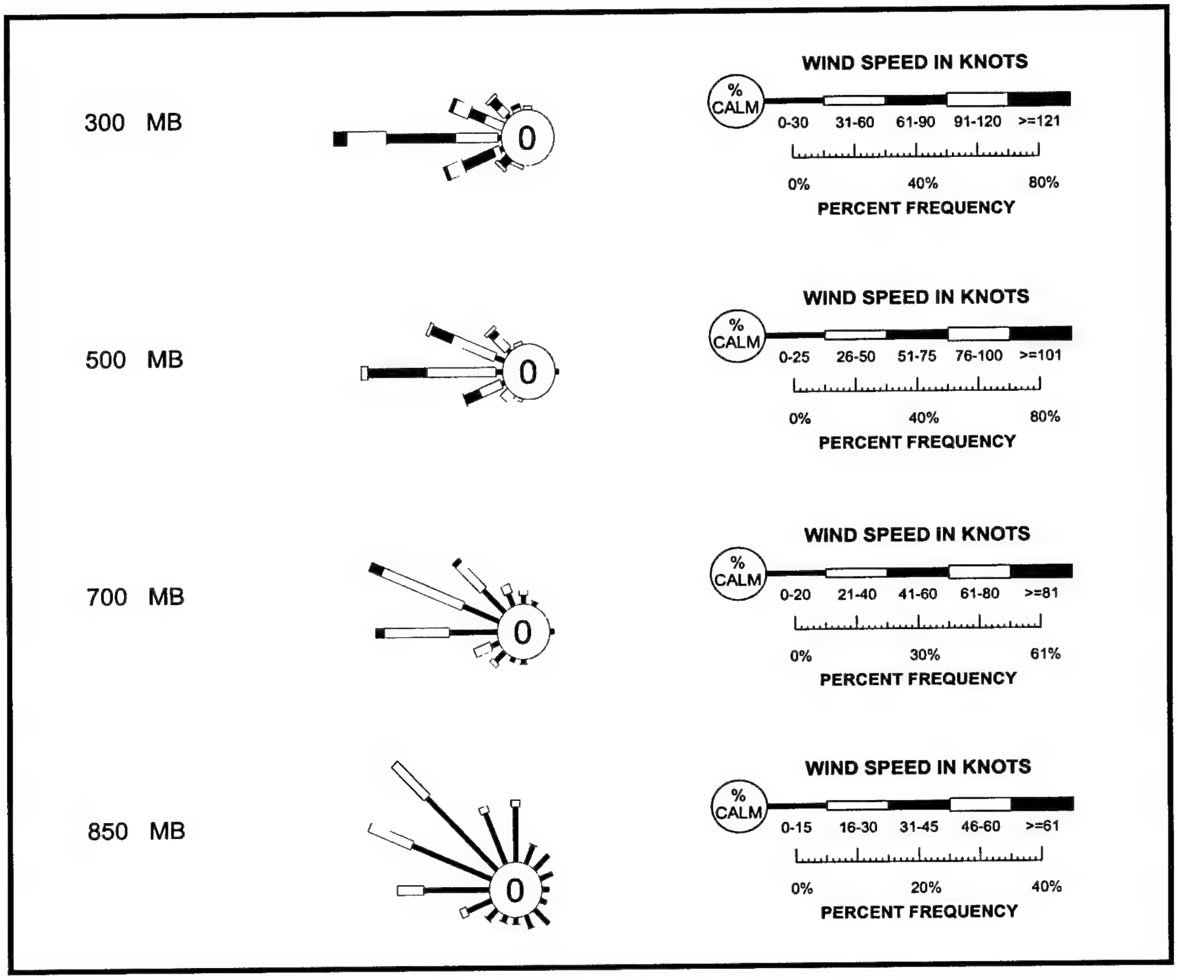


Figure 3-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb over Dacca.

Precipitation. Precipitation is due to passage of lows from the west and occurs chiefly in the mountains and in adjoining lowlands (northern half of the region). This area gets 2-3 inches (51-76 mm) of rain per month. The southern half of the region gets 0.2-0.6 inch (5-15 mm) of rain per month. It rains 1-3 days from November to February and 3-8 days in March. Thunderstorms occur 1-4 days from November to February with a maximum occurrence rate in the eastern half of the Brahmaputra River valley (orographic storms) and in the Bengal basin (Nor'westers). See Figures 3-7 and 3-8 for January mean precipitation amounts and seasonal thunderstorm and rain days, respectively.

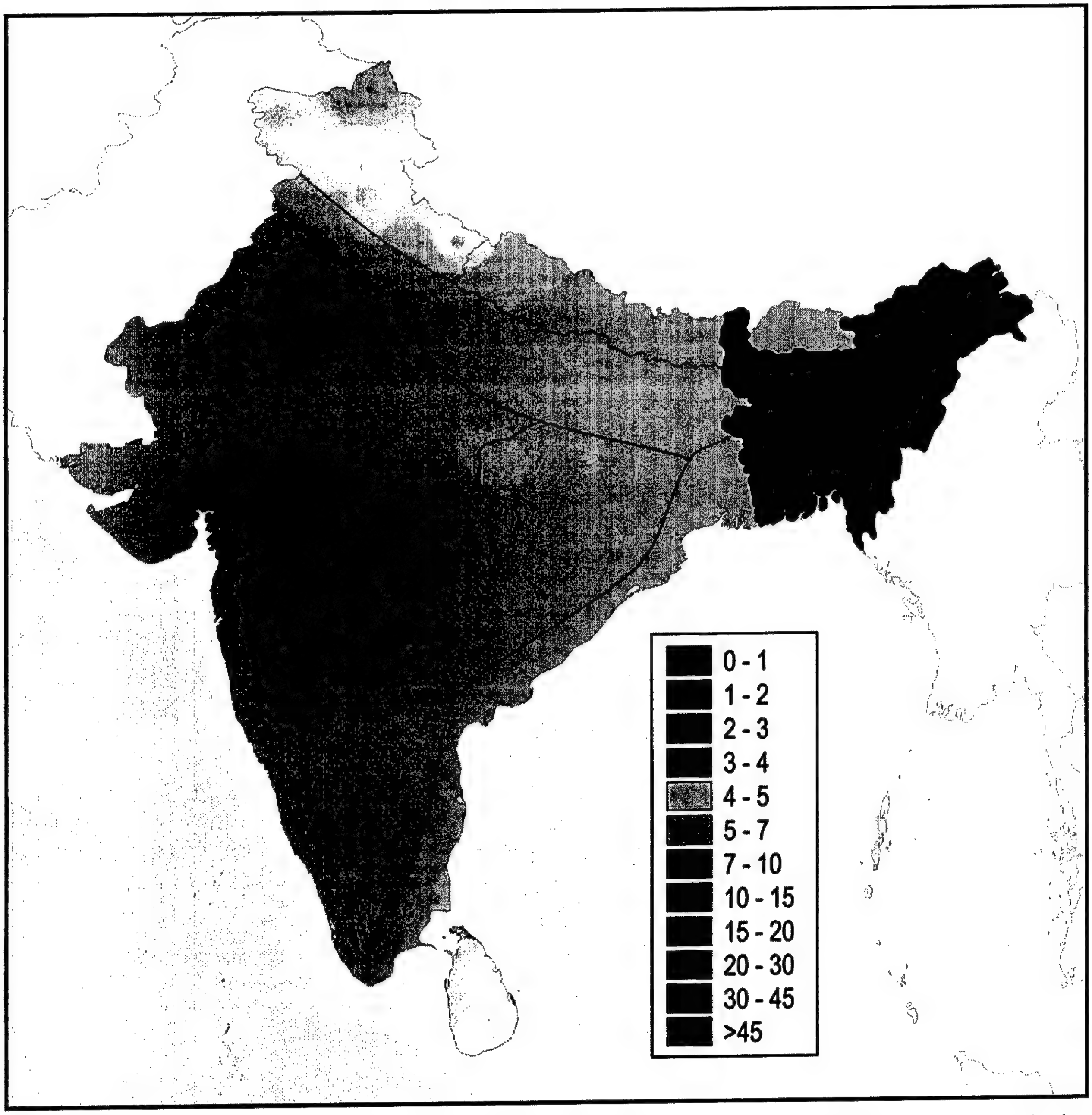


Figure 3-7. January Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

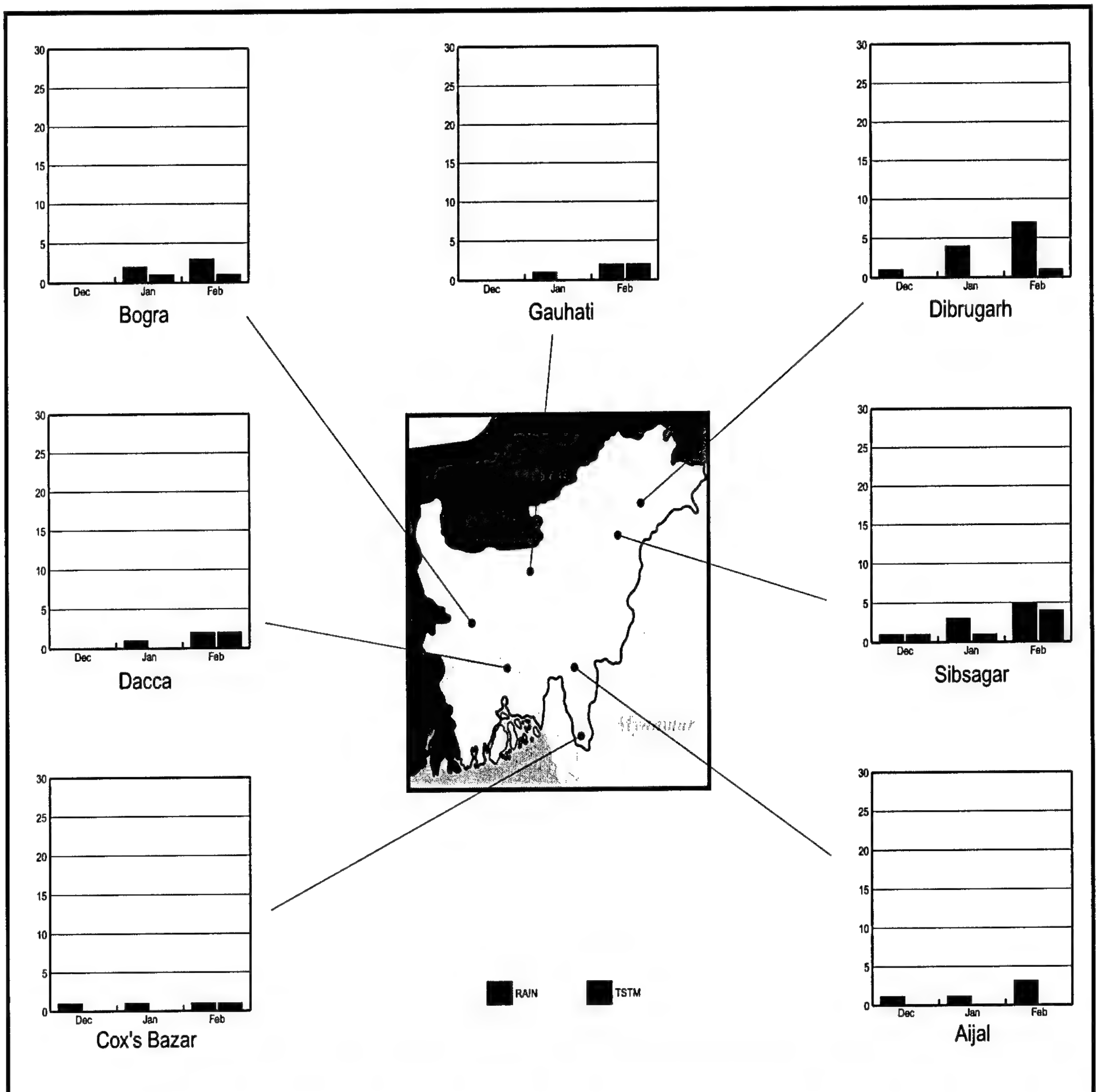


Figure 3-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Winter temperatures are mild. January is the coolest month in most places. The range of temperatures is narrowest in Bangladesh. Over the whole area, mean high temperatures range from 75° to 85°F (24° to 29°C) through the season. Mean lows are 45° to 55°F (7° to 13°C) in higher elevation sites and 55° to 65°F (13° to 18°C) at low elevations. Close to the coast, the mean highs are 82° to 87°F (28° to 31°C); mean lows are around 73° to 78°F (23° to 26°C). Extreme highs are quite hot, between 95° and 100°F (35° to 38°C). Extreme lows are 35° to 40°F (2° to 5°C) in the highlands and 40° to 45°F (5° to 7°C) in lower elevations. Figures 3-9 and 3-10 show the respective mean regional maximum and minimum temperatures for January.

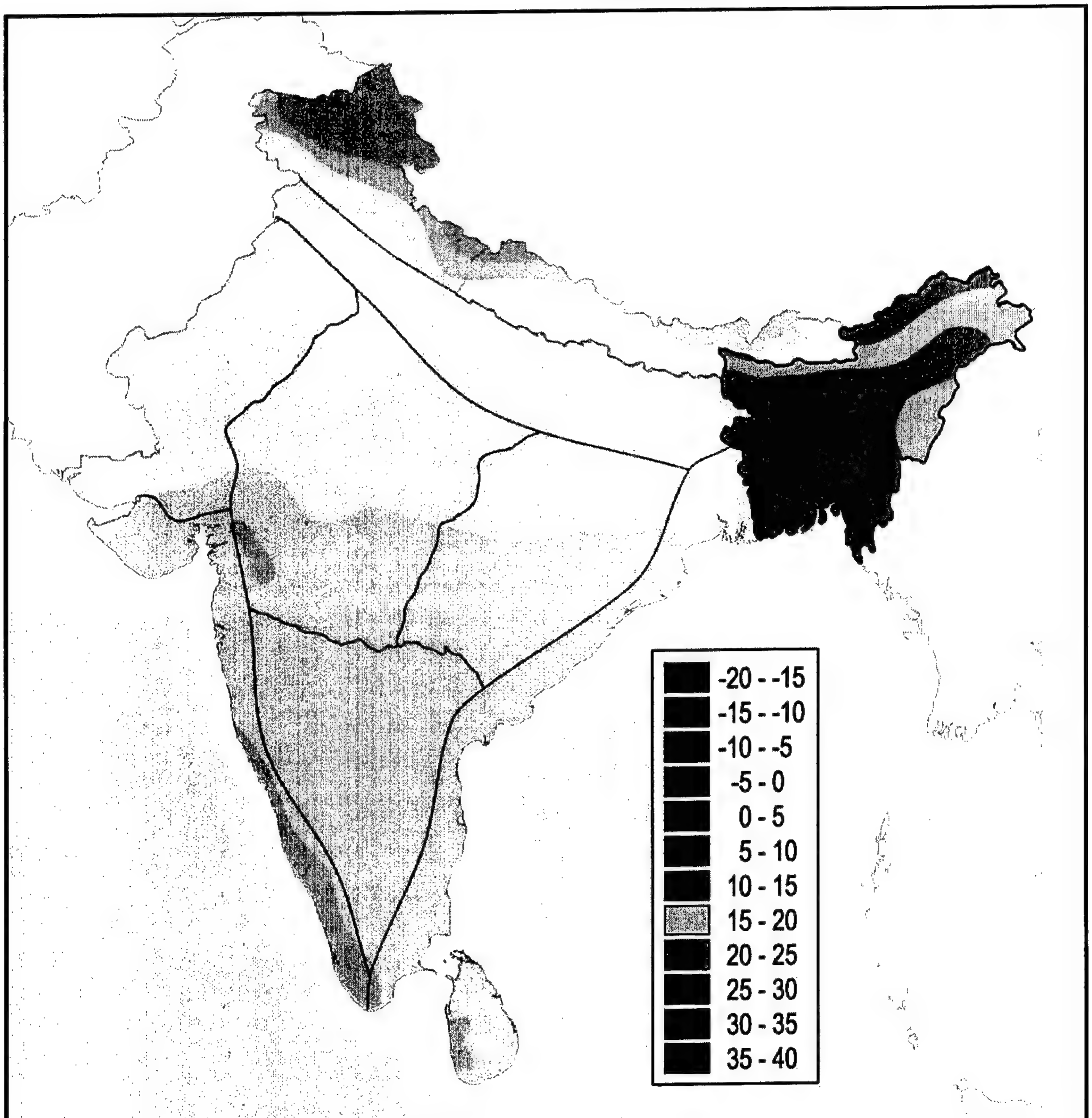


Figure 3-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter months may be lower, especially at the beginning and ending of the season.

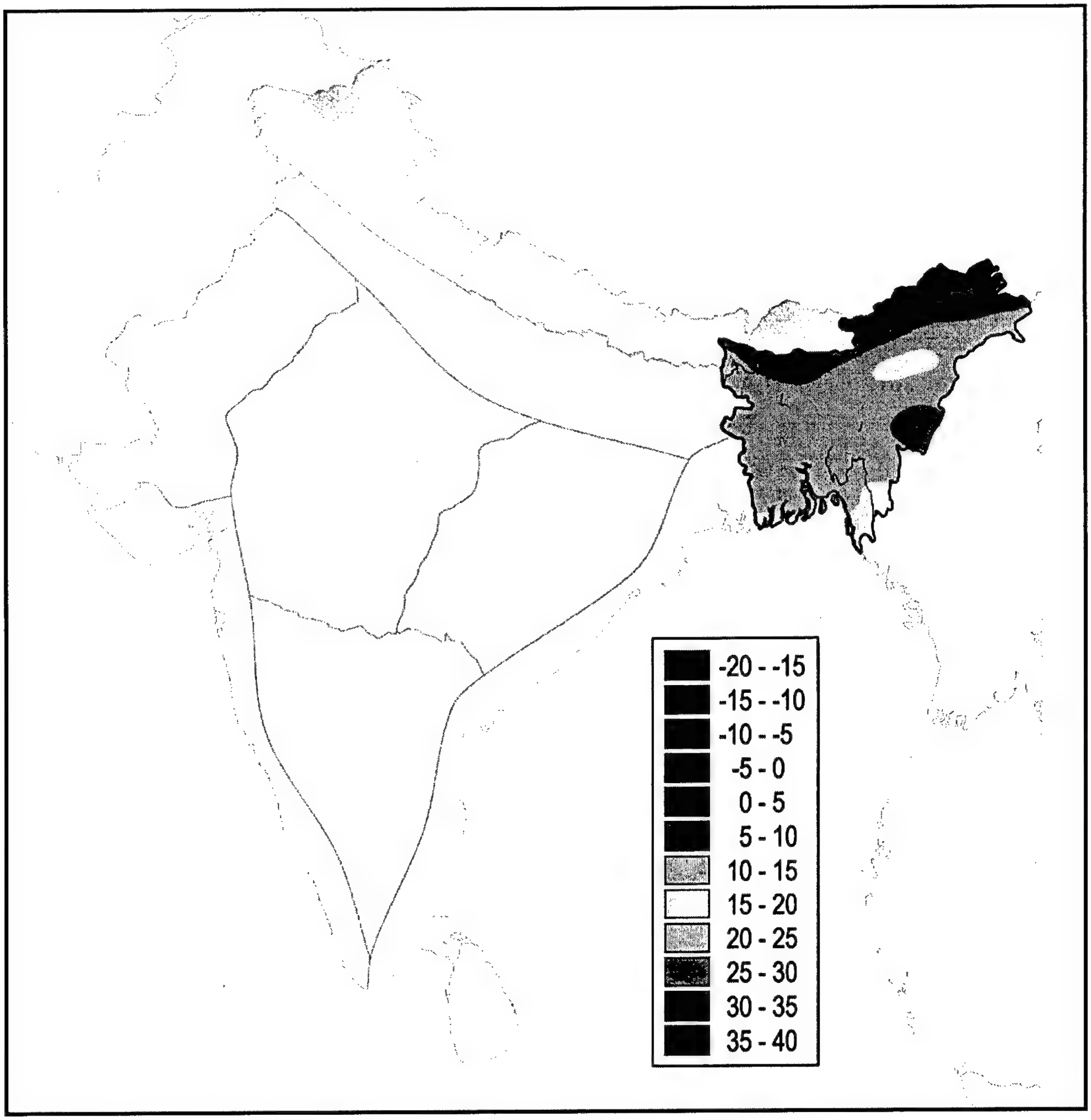


Figure 3-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other winter months may be higher, especially at the beginning and ending of the season.

Hot Season

General Weather. The subtropical jet that moved migratory lows through in the winter has shifted northward and now lies mainly north of the Himalayan massif. Also, the Asiatic high has seriously weakened by March, and the lee-side trough at the southern foot of the mountains is no longer a favored track for passing lows. This moves the storm track from the southern flanks of the Himalayas to north of the range, and few lows move across northern India as a result. The Australian low disappears in this phase, and the equatorial trough (ET) heads northward with the sun. Wind circulation is confused and largely locally driven. Generally, the weather is clearest and driest in these months; the hottest temperatures occur now.

There is considerable variance in onset of the southwest monsoon across the region. The rains begin in the northeast corner of the Bengal basin to East India in mid-May. It takes another month and a half for all of India to be fully under the southwest monsoon. The northward travel of the ET is not a smooth one. It oscillates north and south, moves many miles in surges then retreats, and stagnates in one place for days at a time. In this transition season, "onset vortices" travel along the ET at the leading (northern) edge of the southwest monsoon air mass. These vortices produce rain, rainshowers, and thunderstorms and signal the "monsoon burst" of the changing season. The hottest weather of the year ends with this transition as cloudiness and rain come to cool the land.

Western disturbances occur mostly in winter and early hot season (November to April). They follow the lee-side trough at the southern foot of the Himalayas and are driven by the STJ. They move from west to east and give rise to cloudiness and precipitation. This is also when Nor'westers are most common. They occur in the Ganges plain between the western end of the Khasi Hills and the Eastern Ghats. These storms form in the convergence between cooler, drier flow from the Brahmaputra River valley and the warmer, moist flow of the Bay of Bengal. These squalls can generate high downrush gusts, 40-50 knots (on rare occasions, over 100 knots), and occasional tornadoes. Nor'westers occur in spells; they sometimes occur at the same time of day in the same area 4-5 days in a row. They almost always occur in the late afternoon or early evening on a warm, humid day, last 3-4 hours, and are followed by clear, cool weather. The arrival of the southwest monsoon ends them.

April-May is the annual secondary peak period for tropical cyclones and other storms. Bay of Bengal storms develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Early easterly waves, and onset vortices also grow into storms over the warm waters of the bay.

Sky Cover. Cloud cover is limited early in this season but increases between April and May with the approach of the southwest monsoon. Low cloudiness increases in the latter half of May. Along the coast, stratocumulus occurs in the early morning and evening hours but scatters during the day. In the interior, afternoon cumulus develops during the day but dissipates after sundown. On the coast, ceilings at 2,000-4,000 feet occur more in the mornings. Inland, ceilings at 3,500-6,000 feet occur more in the afternoons.

On the coast, morning ceilings below 5,000 feet occur 5-10 percent of the time in March, 15-20 percent of the time in April, and 35-40 percent of the time in May. The rest of the day, coastal ceilings below 5,000 feet occur 5-10 percent of the time in March and April and 10-15 percent of the time in May (see Figure 3-11). Inland on the plain, March and April ceilings below 5,000 occur 5-10 percent of the time. In May, they occur 20-30 percent of the time. In the Brahmaputra River valley, occurrence depends on position relative to wind. In March and April, ceilings below 5,000 feet occur 10-15 percent of the time in leeward locations and 35-45 percent of the time in windward sites. By May, all ceiling occurrence rates rise. In leeward places, they occur 25-35 percent of the time and in windward places, 55-65 percent of the time. In the mountains, ceilings vary with elevation. Ceilings below 5,000 feet occur 5-10 percent of the time in March and April and 25-35 percent of the time in May. In places directly in the wind, rates are higher, 15-20 percent of the time in March, 35-45 percent of the time in April, and 65-75 percent of the time in May.

Ceilings below 1,000 feet rarely occur in most of the region. Only the windward sites in the Brahmaputra River valley, such as Sibsagar, get them. There, they occur 40-50 percent of the time in the morning and 15-25 percent of the time the rest of the day. At Imphal, in a high, marshy, river valley in the eastern mountains, ceilings below 1,000 feet occur rarely in March and April but occur 9-14 percent of the time in May, with the most in the morning.

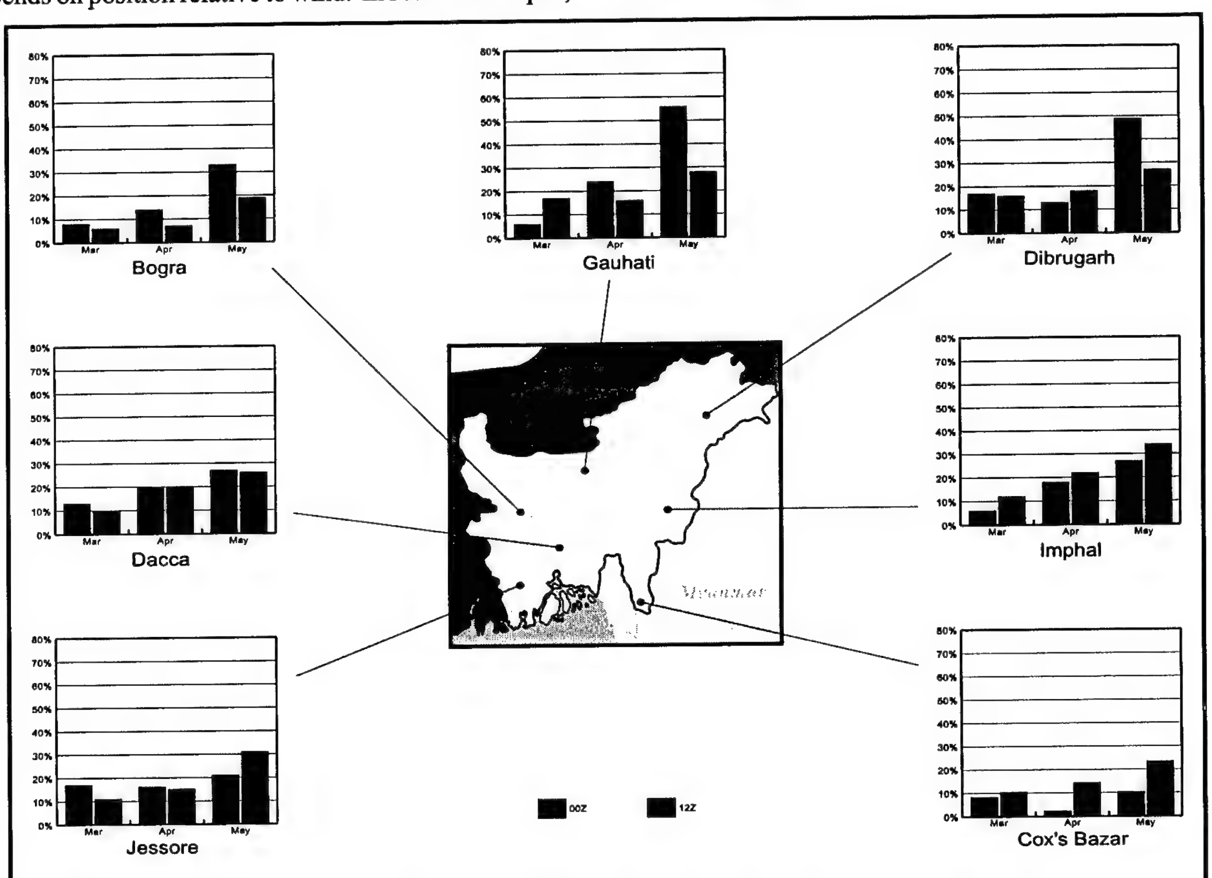


Figure 3-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Dust haze restricts visibility more in this season than any other, especially in the Ganges Plain, where fine-grained alluvial soil dominates. During a dry squall, dust is often lifted hundreds of feet and can become quite dense. Fine dust will remain suspended for a long time. Dust storms are most frequent during the afternoons but can occur at any time of day.

Visibility below 2 1/2 miles (4,000 meters) does not occur often in the lowlands of the Bengal basin, but the Brahmaputra River valley gets it, more in March than in April or May. The windward sites in the eastern half of the valley have morning visibility below 4,000 meters 35-45 percent of the time in March and 25-30 percent of the time in April and May. In the western Brahmaputra valley, windward sites have it 30-40 percent of the time in March, 20-25 percent of the time in April, and 10-15 percent of the time in May. Leeward sites throughout the valley have visibility below 4,000 meters 5-10 percent of the time in the mornings, most in March and least in May. By midday, conditions improve and few places have visibility below 4,000 meters. Even Sibsagar, notoriously foggy, has afternoon visibility below 4,000 meters only 22 percent of the time in March and under 15 percent of the time in April and May. See Figure 3-12.

Visibility below 1 1/4 miles (2,000 meters) rarely occurs in most of the region. The windward Brahmaputra River valley sites get it in the mornings 5-10 percent of the time in March and April and 10-15 percent of the time in May. The eastern stations have the higher rates. By noon, the conditions improve; even Sibsagar does not get visibility below 2,000 meters in March or April and only 8 percent of the time in May.

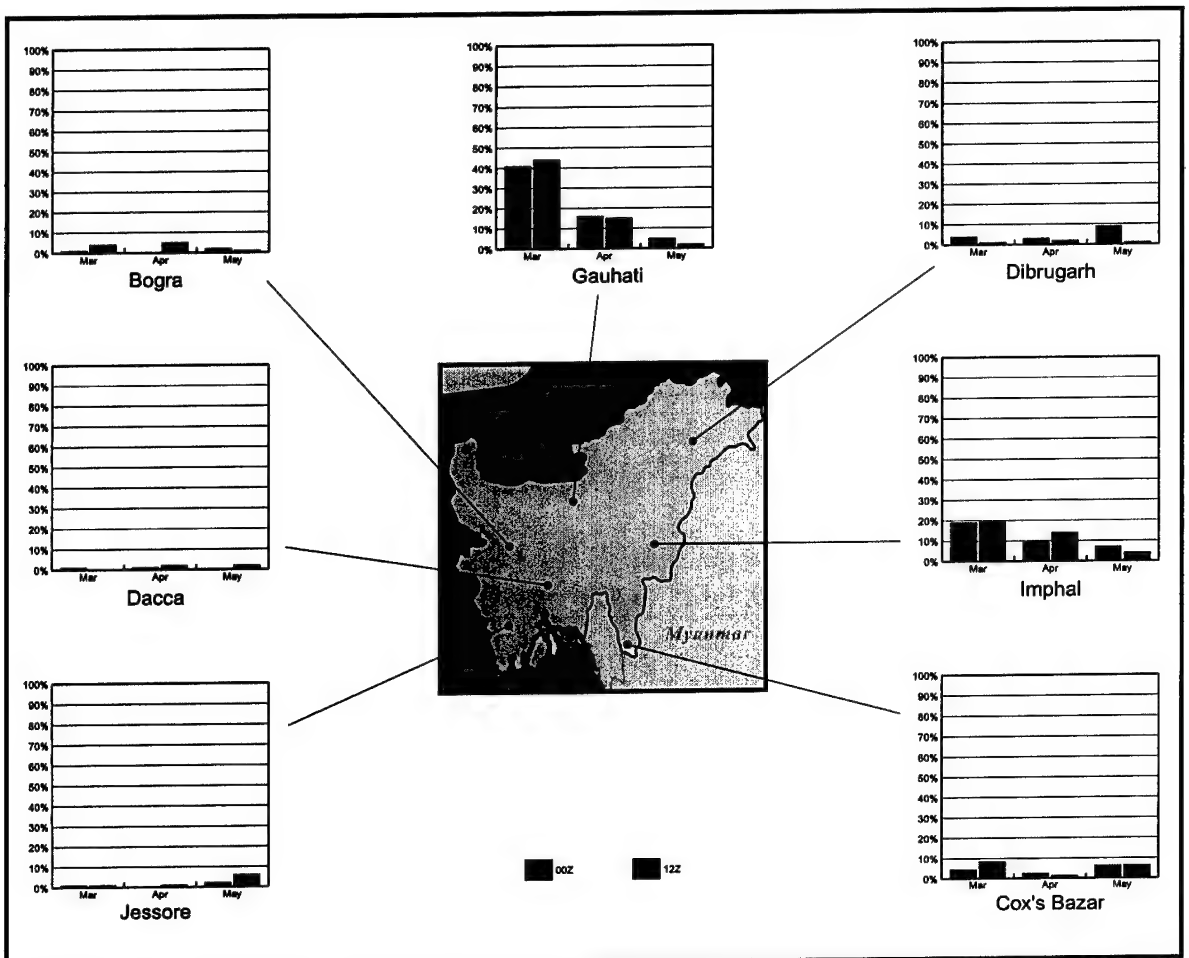


Figure 3-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The season begins with northeasterly large-scale flow and ends with southwesterly flow. Large-scale flow is in transition so local effects tend to dominate the wind flow. Cooler, drier northeast winds flow out of the Brahmaputra River valley at 5-10 knots. Cool air descends from the mountains and drains down the river valley and around the west end of the Khasi Hills. In the Bengal plain, which includes most of Bangladesh, the sea breeze reaches far inland. In the evening through morning hours, the winds are from the north at 5 knots or less. During the afternoons, on the coast first, the winds are from the south at 5-10 knots. On the eastern coast, the land/sea breeze also dominates, but by May, southerly winds begin to override the night land breeze. The closer to the sea, the stronger the winds. Mountain site winds vary locally with terrain. In the eastern mountains, the north-south oriented ridges direct flow but some mountain/valley slope effect occurs as well. Figure 3-13 shows April surface winds around the region.

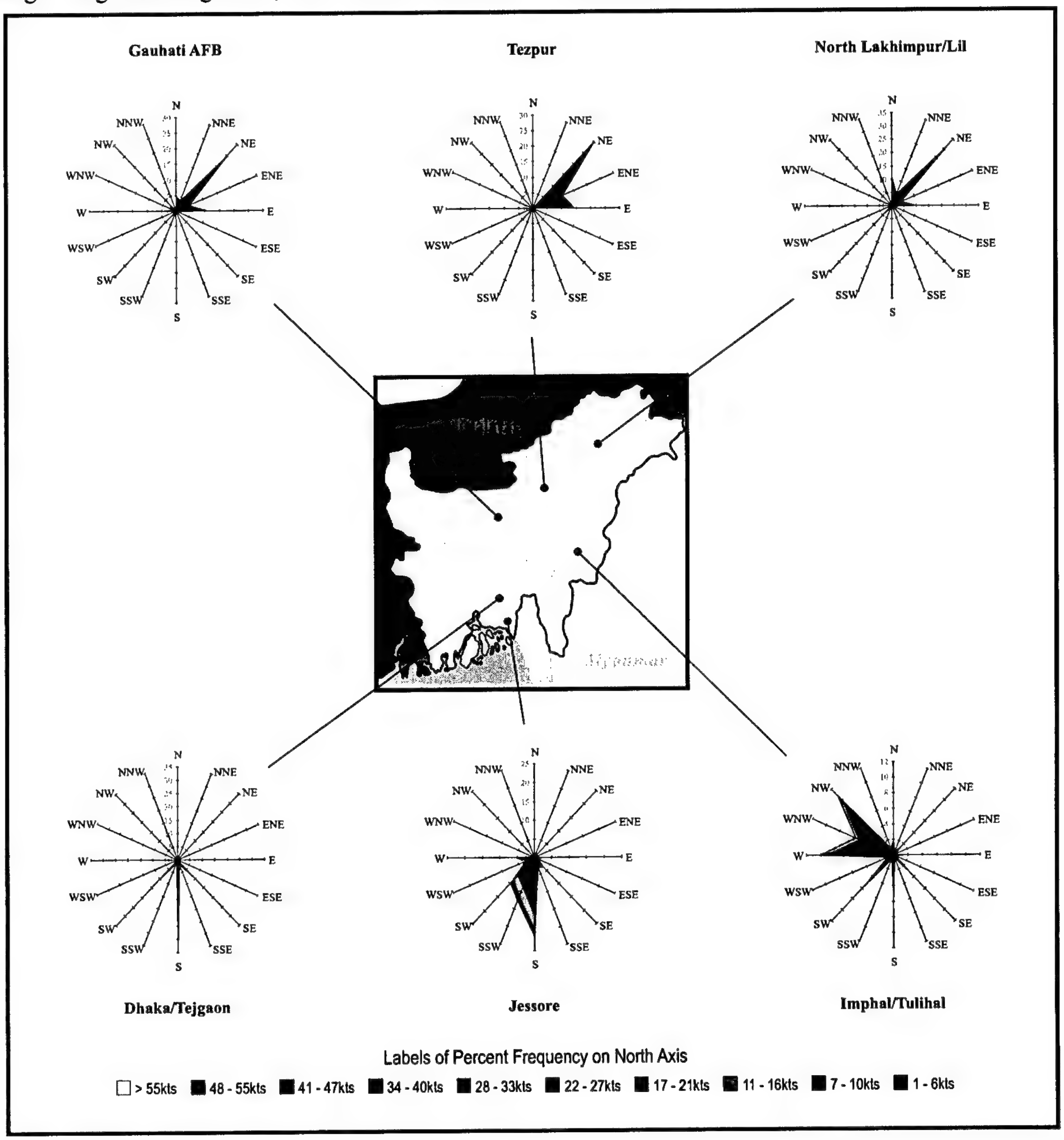


Figure 3-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. From March through May, 850 mb winds are northwesterly at 10-15 knots. At 700 mb, west winds at 25 knots in March shift to northwest winds at 15-20 knots by April. At 500 mb, west to northwest winds at 35-40 knots prevail. At 300 mb, west winds at 65-70 knots blow all season. See Figure 3-14 typical April upper-air winds over Dacca.

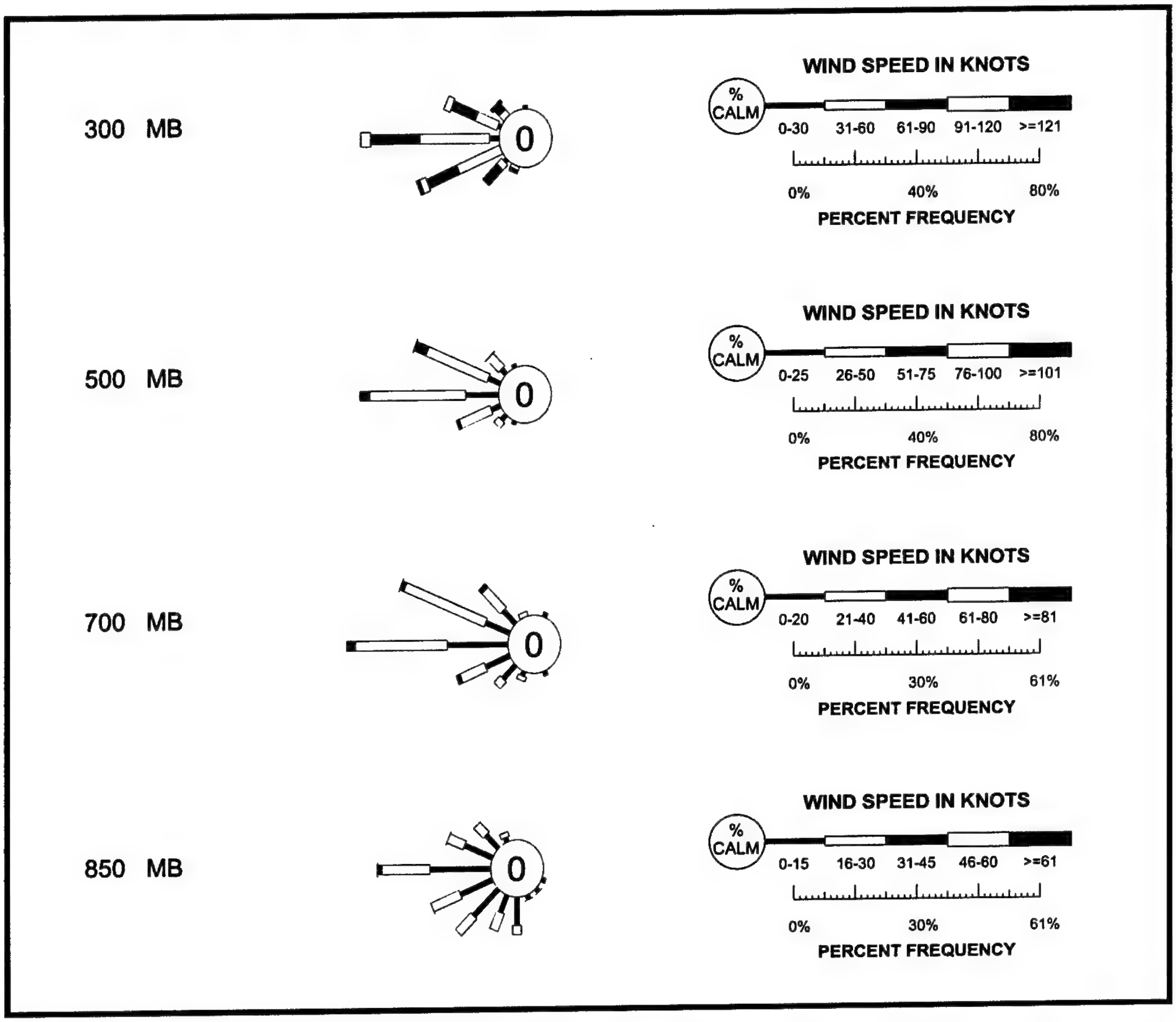


Figure 3-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Dacca.

Precipitation. Precipitation occurs chiefly with thunderstorms. Moderate to large amounts of rain fall only in the eastern part of the area. Over most of the rest of the area, less than one inch (25 mm) falls per month. Rain falls 1-5 days in lee locations of the eastern thunderstorms. In the Brahmaputra River valley, orographic lift under unstable upper-air flow is largely responsible. In the Bengal basin, Nor'westers are fired by cooler flow from the Brahmaputra valley that collides with warmer air from the bay. Thunderstorms occur 2-5 days in April and May in most places. In the Bengal plain and the southern slopes of the Khasi Hills, thunderstorm activity rises sharply in May to 8-12 days. Figures 3-15 and 3-16 show the April mean precipitation amounts and seasonal thunderstorm and rain days, respectively.

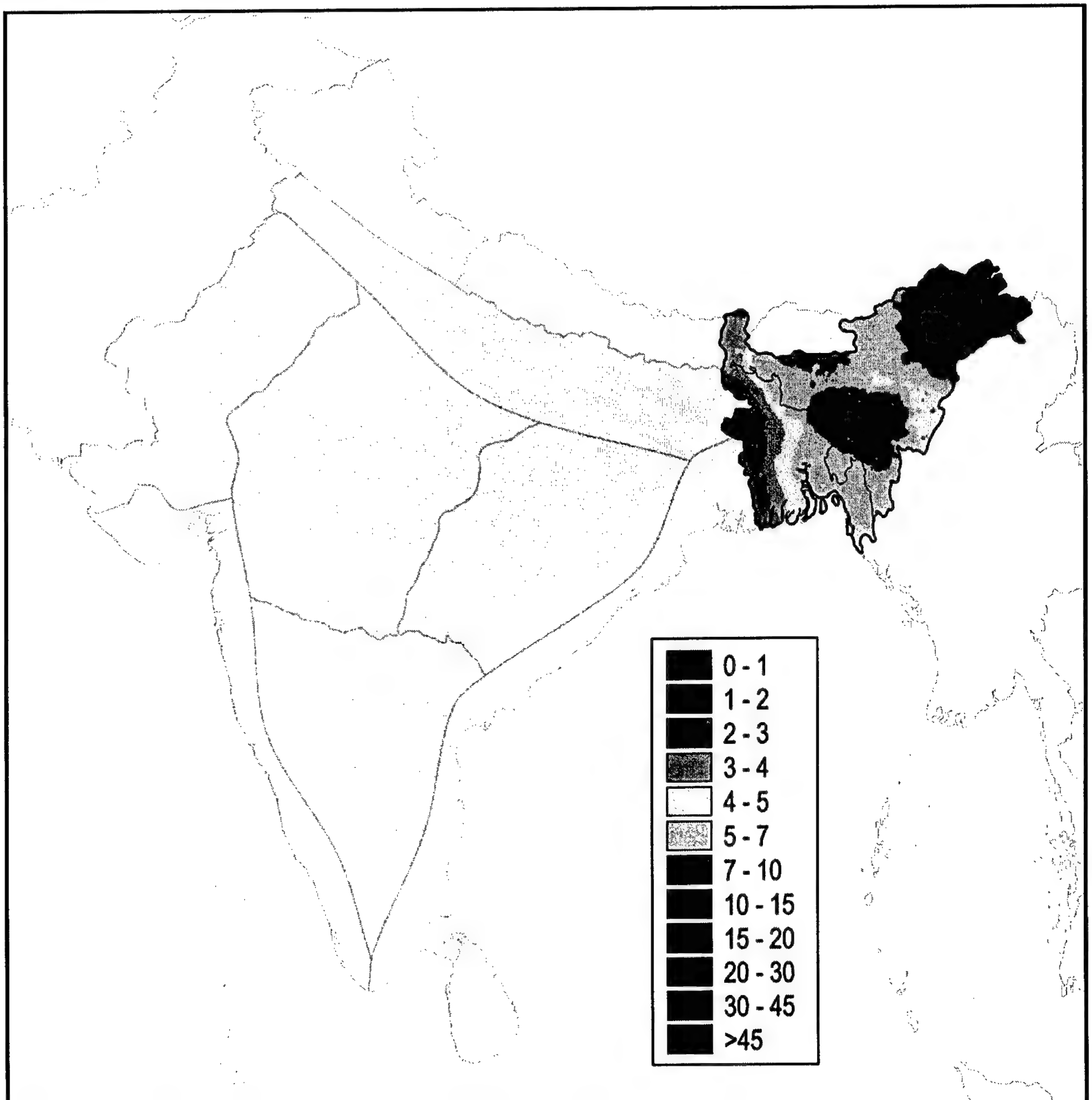


Figure 3-15. April Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

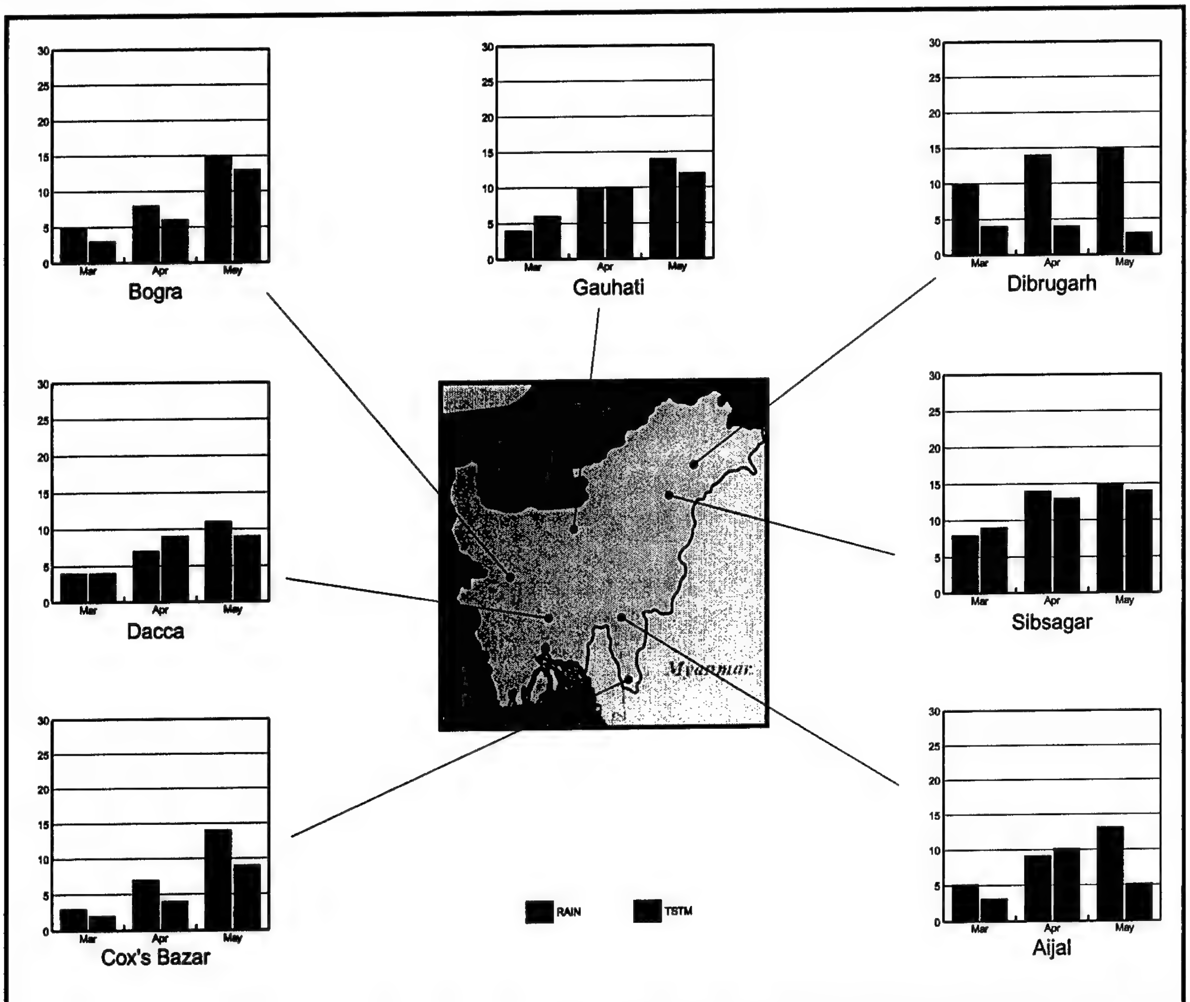


Figure 3-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. This season has a continuous rise in temperature until the southwest monsoon arrives. Mean highs are 85° to 92°F (29° to 33°C) in March and the warmest period is generally mid-April to late May with mean maximums in the 94° to 98°F (34° to 37°C) range. Figure 3-17 shows the regional April mean maximum temperatures. The mean lows are 60° to 70°F (16° to 21°C) in March, 65° to 75°F (18° to 24°C) in April (see

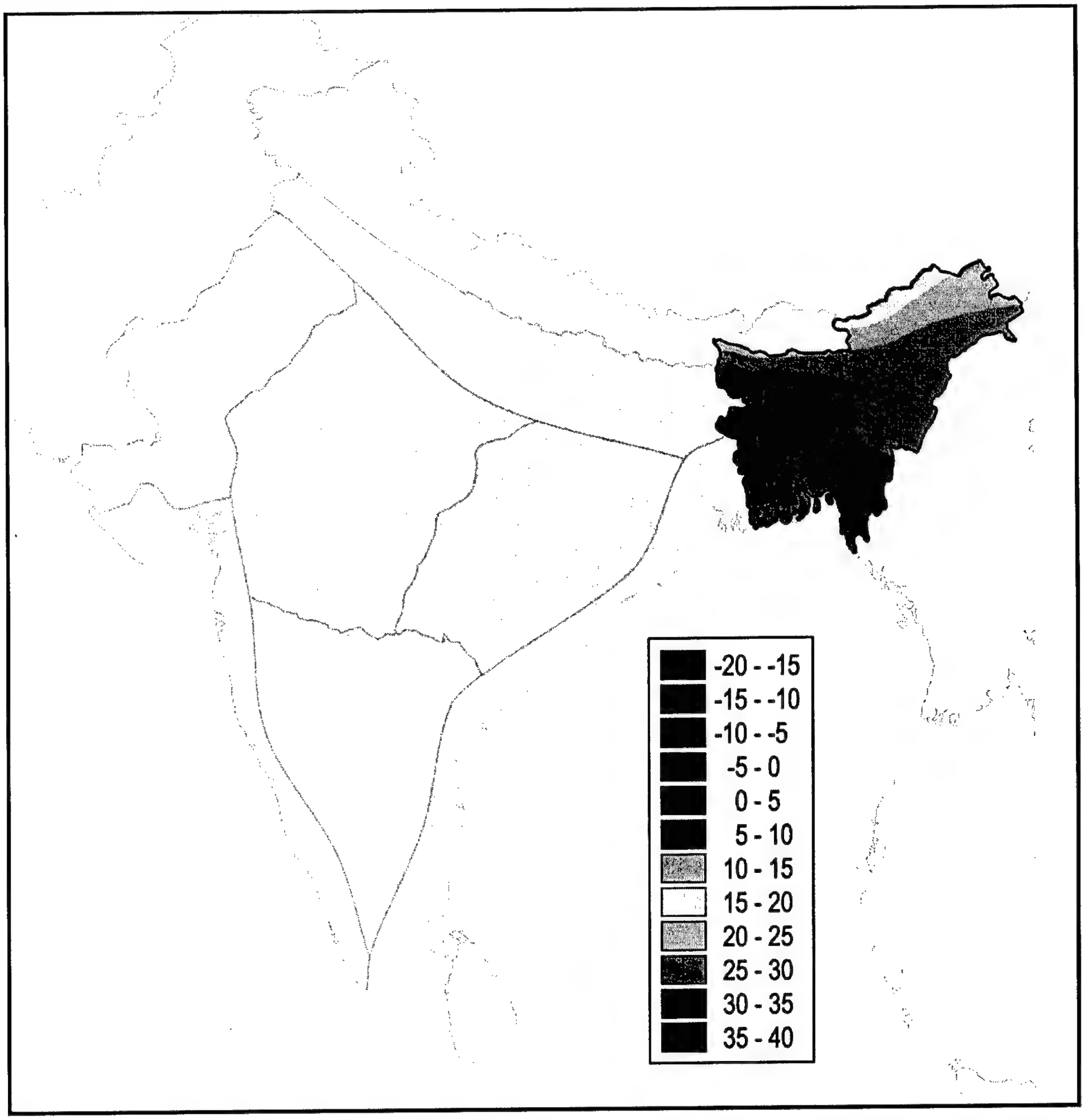


Figure 3-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Figure 3-18), and 75° to 80°F (24° to 27°C) in May. Except in the highlands, the extreme high temperature exceeds 120°F (49°C). In the highlands, the extreme highs are 100° to 105°F (38° to 41°C) The extreme lows are 55° to 65°F (13° to 18°C) in the lowlands and 45° to 55°F (7° to 13°C) in the highlands.

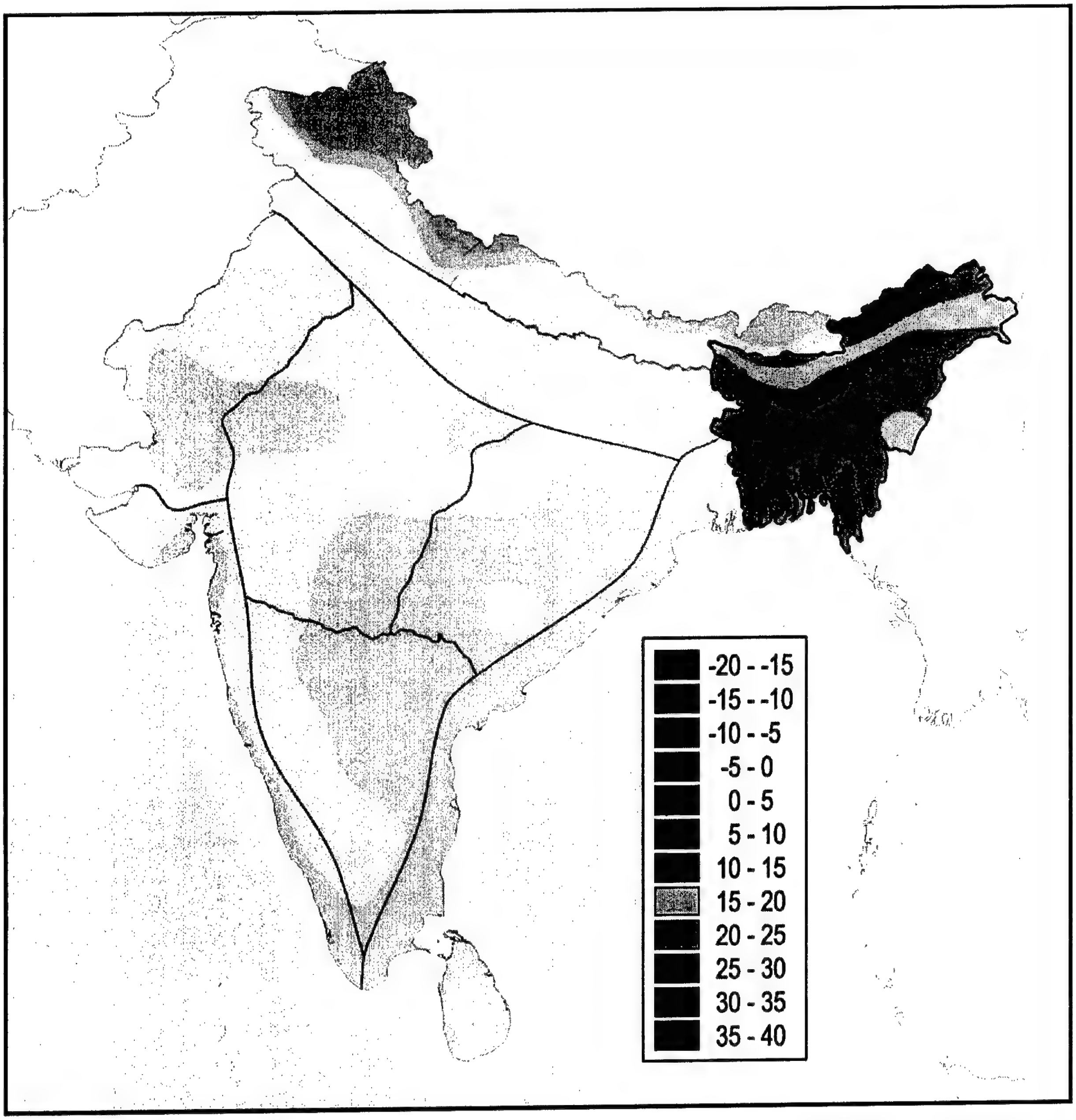


Figure 3-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. The equatorial trough (ET) moves into the area along with overall southwest flow. Although generally considered to begin in June, the monsoon can begin in mid-May. By the end of July, the whole of South Asia is under southwest monsoon flow. By July and August, the ET is as far north as it gets, and easterly flow aloft is to the foot of the Himalayas. The India-Myanmar trough sets up in this season. This northeast-southwest oriented trough develops over the Bay of Bengal and is a prime breeding ground for monsoon depressions. Easterly waves and other tropical disturbances are enhanced when they make their way into this convergence zone and sometimes develop into full-blown tropical cyclones. The official tropical cyclone season is June to November.

The equatorial westerlies are a hallmark of the southwest monsoon season. Created by the deflected outflow of the South Indian Ocean high, these low-level winds spread out over the north Indian Ocean. At the same cyclones, monsoon depressions, and other cyclonic storms. Fortunately, storms in the Bay of Bengal are so confined, they do not become as powerful as open ocean storms. They still carry high winds, heavy surf, and vast amounts of precipitation to the coasts.

The deep, wide band of upper-air easterlies overlay the equatorial westerlies. During this season, the easterlies are strongest and spread farthest north. Easterly waves ride this powerful current of air and trigger monsoon depressions and tropical cyclones. By the end of the season, the band of easterlies retreats southward. This is also when thermal lows set up over the central Indian subcontinent and over the Tibetan Plateau. The Indian low becomes part of the greater Asiatic low and trough. This is a source region for migratory lows that move across the subcontinent and into the Bay of Bengal. Overlying the Tibetan low is the Tibetan anticyclone, which develops in the zone between the strong, deep westerlies of the Northern Hemispheric mid-latitudes and the strong, deep easterlies of the low latitudes. The stronger the thermal low, the stronger the anticyclone. The southern edge of this anticyclone is a prime area for the development of monsoon depressions and other cyclonic storms, especially in the Bay of Bengal.

Sky Cover. Cloud cover is at its peak. Cloud cover and type are both determined by terrain in the humid airflow. Cloud cover is mostly low and mid-level stratiform types. Most ceilings are between 2,000 and 3,000 feet.

Most places have morning ceilings below 5,000 feet 60-70 percent of the time in June through August and 35-45 percent of the time in September. The rest of the day, ceilings below 5,000 feet occur 35-45 percent of the time in June through August and 20-30 percent of the time in September. Sibsagar gets them as much as 90 percent of the time in the mornings and 60-65 percent of the time the rest of the day all season. A few places, such as Tezpur (on the north bank of the Brahmaputra River), only have them 25-35 percent of the time in the mornings and 10-15 percent of the time the rest of the day. Since the winds tend to flow west down the valley all year, the low ceilings on the south side of the river do not affect the north banks as much. See Figure 3-19 for seasonal percent frequency of ceilings below 5,000 feet.

Morning ceilings below 1,000 feet do not occur often in most places, generally 5-10 percent of the time or less. Dacca, an exception on the Bengal plain, gets them 22 percent of the time in June, 15 percent of the time in July and August, and 7 percent of the time in September. By noon, these ceilings burn off and occur 5-10 percent of the time. Only places like Sibsagar and Imphal get ceilings below 1,000 feet often. At Imphal, they occur 30-40 percent of the mornings all season. At Sibsagar, they occur 40-50 percent of the mornings every month but August, when the rate rises to 60 percent of the mornings. A few places at the west end of the Khasi Hills get them 25-35 percent of the mornings in June through August and 15 percent of the time in September. By afternoon, the ceilings occur 20-25 percent of the time at Sibsagar and 15-20 percent of the time at Imphal until September when it drops to under 5 percent of the time.

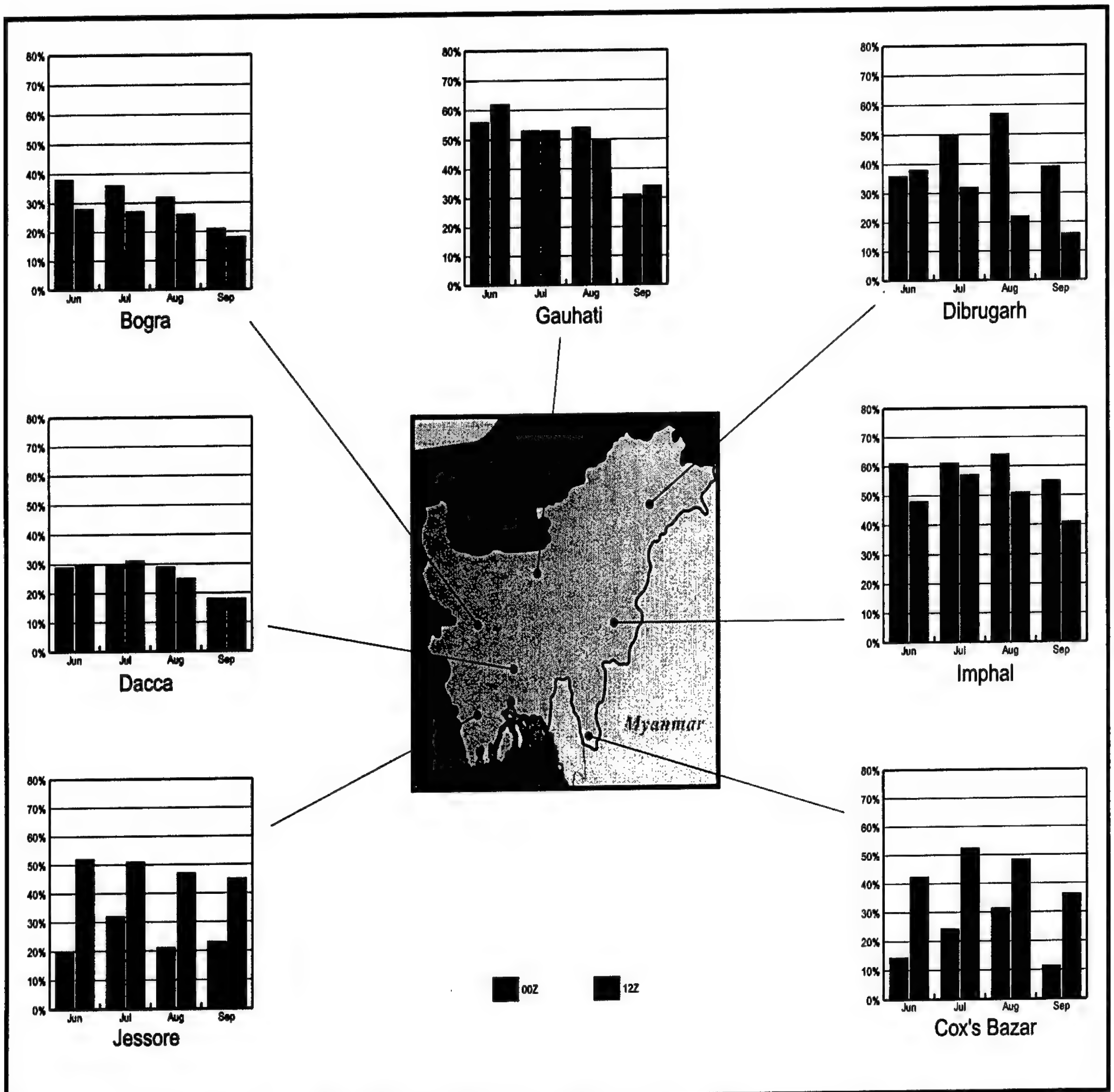


Figure 3-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is mainly reduced by rain. Moist haze persists even when it is not raining. Prolonged, heavy rains can reduce visibility below 3 miles (4,800 meters) for extended periods. Although hill stations report fog all year, the highest frequencies occur during this season. These "mountain fogs" are low clouds that cloak higher elevations.

Visibility below 2 1/2 miles (4,000 meters) occurs in coastal and leeward places under 5 percent of the time. Windward places have it 20-30 percent of the time in the morning and 15-25 percent of the time the rest of the day. Even there, visibility improves in September to 10-15 percent of the time in the mornings and under 10 percent of the time the rest of the day. Aijal, on a ridge between two higher peaks in the eastern mountains, is an exception. There, visibility below 4,000 meters occurs 20-25 percent of the time in the mornings. The rate increases to 28 percent of the time the rest of the day in June and July, peaks at 40 percent of the time in August, and drops to 16 percent of the time in September. This is caused by terrain lifting of moisture. Figure 3-20 illustrates the seasonal percent frequency of ceilings below 5,000 feet.

Visibility below 1 1/4 miles (2,000 meters) occurs rarely in most places. Even Sibsagar gets it only 10 percent of the mornings and rarely the rest of the day. Aijal gets it as much as 25 percent of the time in the mornings and up to 38 percent of the time in June afternoons. The afternoon occurrence rate there drops from 25 percent of the time in July and August to 16 percent of the time in September.

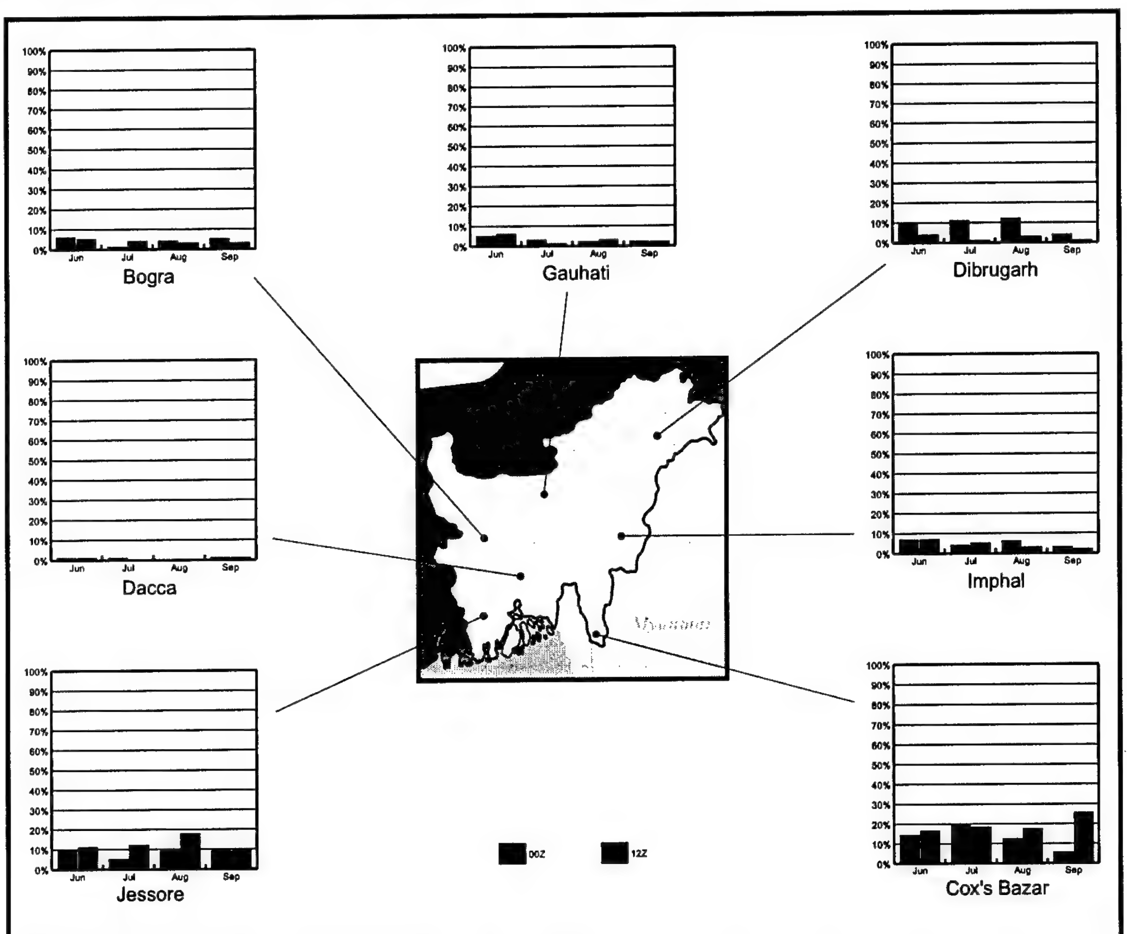


Figure 3-20. Southwest Monsoon Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Winds in the Bengal plain are mainly from the south and stronger on the coast than inland. Average speed inland is 5-10 knots while the coast has 8-12 knots. Winds are stronger during the day than at night as the sea breeze augments the southwest monsoon flow, and the land breeze, although overwhelmed by monsoon flow, damps it slightly. In the Brahmaputra River valley, winds blow from the northeast all year at 5-10 knots. In the mountains, position relative to terrain and to synoptic flow determines the winds at any one place. Imphal, in a north-south valley between ridges, has light winds equally from the southeast and the northwest in terrain-steered flow modified by downslope from the mountains. Large-scale flow in this region is from the south-southwest. Figure 3-21 depicts surface wind roses in July for various regional locations.

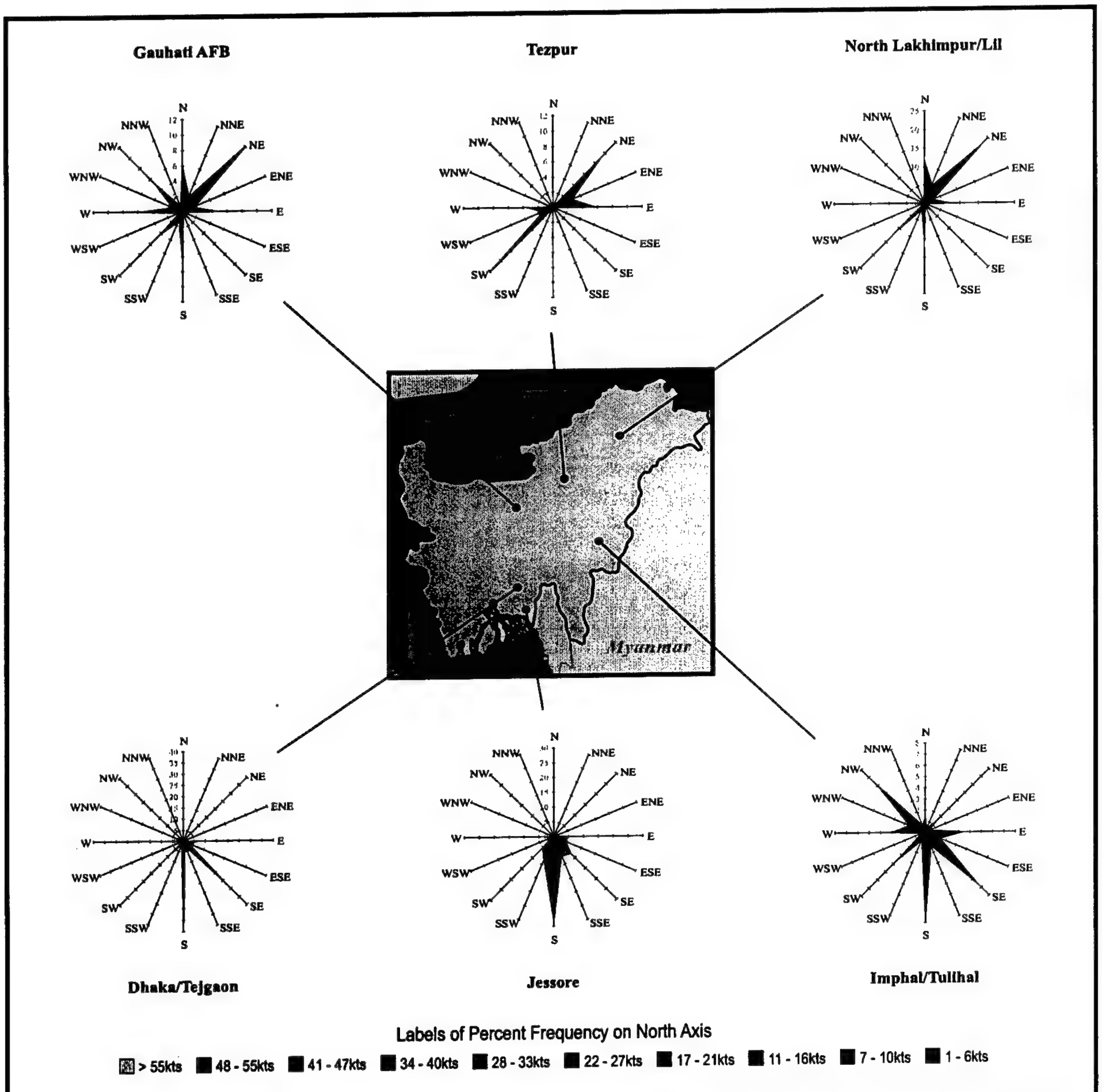


Figure 3-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Winds at 850 mb are variable at 5-10 knots. The June 700-mb winds are from the northwest at 10 knots. By July, the winds come from the southeast-southwest at 10 knots and remain from that direction the rest of the season. At 500 mb, the winds start the season variable at 5-10 knots and eventually settle to southeast-southwest winds by August. The 300-mb winds come from the southeast-southwest at 10-15 knots in June and July then shift to east at 15-20 knots in August then to south at 10 knots in September. See Figure 3-22 for Dacca upper-air wind roses in July.

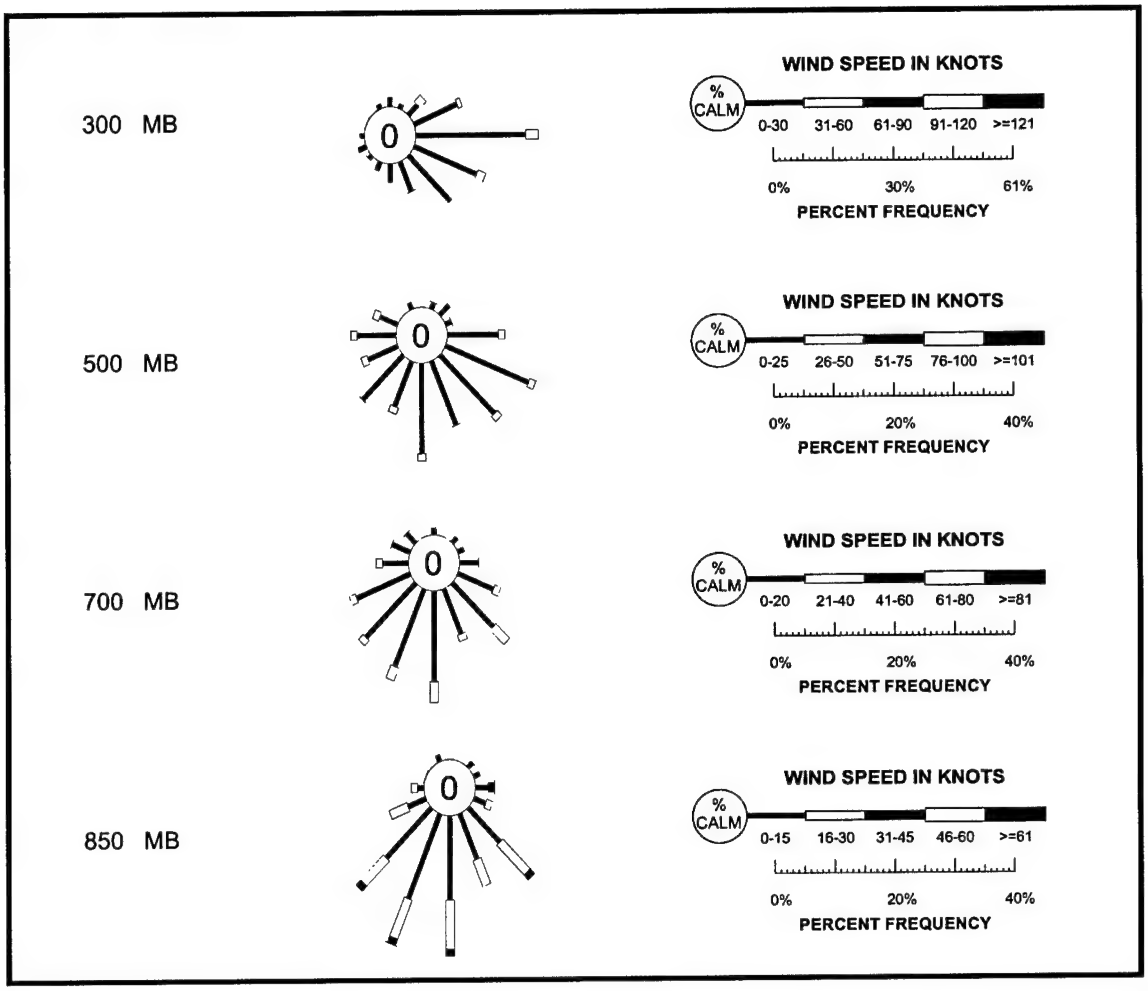


Figure 3-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Dacca.

Precipitation. By the first part of June, the southwest monsoon bursts onto the area. Downpours prevail through August or September. Most of the rain is associated with tropical depressions that form at the head of the Bay of Bengal and move up the Bengal basin along the India-Myanmar trough or is with onshore advection of moist southwest monsoon air. Although rain falls copiously, violent thunderstorms are not common once the initial "monsoon burst" has passed. The period of June-September provides 60-75 percent of the rain for the eastern highlands and up to 90 percent of the rain for the Bengal basin and the southern uplands between the two areas. The Khasi Hills get huge amounts of rain during this season because of upslope. The monthly average in the hills is 40-50 inches (1,016-1,270 mm). Cherrapunji is an exception; it gets 67 inches (1,702 mm) in May, 113 inches (2,870 mm) of rain in June, 97 inches (2,464 mm) in July, 72 inches (1,829 mm) in August, and 49 inches (1,245 mm) in September. It gets this because of terrain funneling and upslope. In the eastern highlands, the average rainfall from May to September is 10-20 inches (254-508 mm) per month.

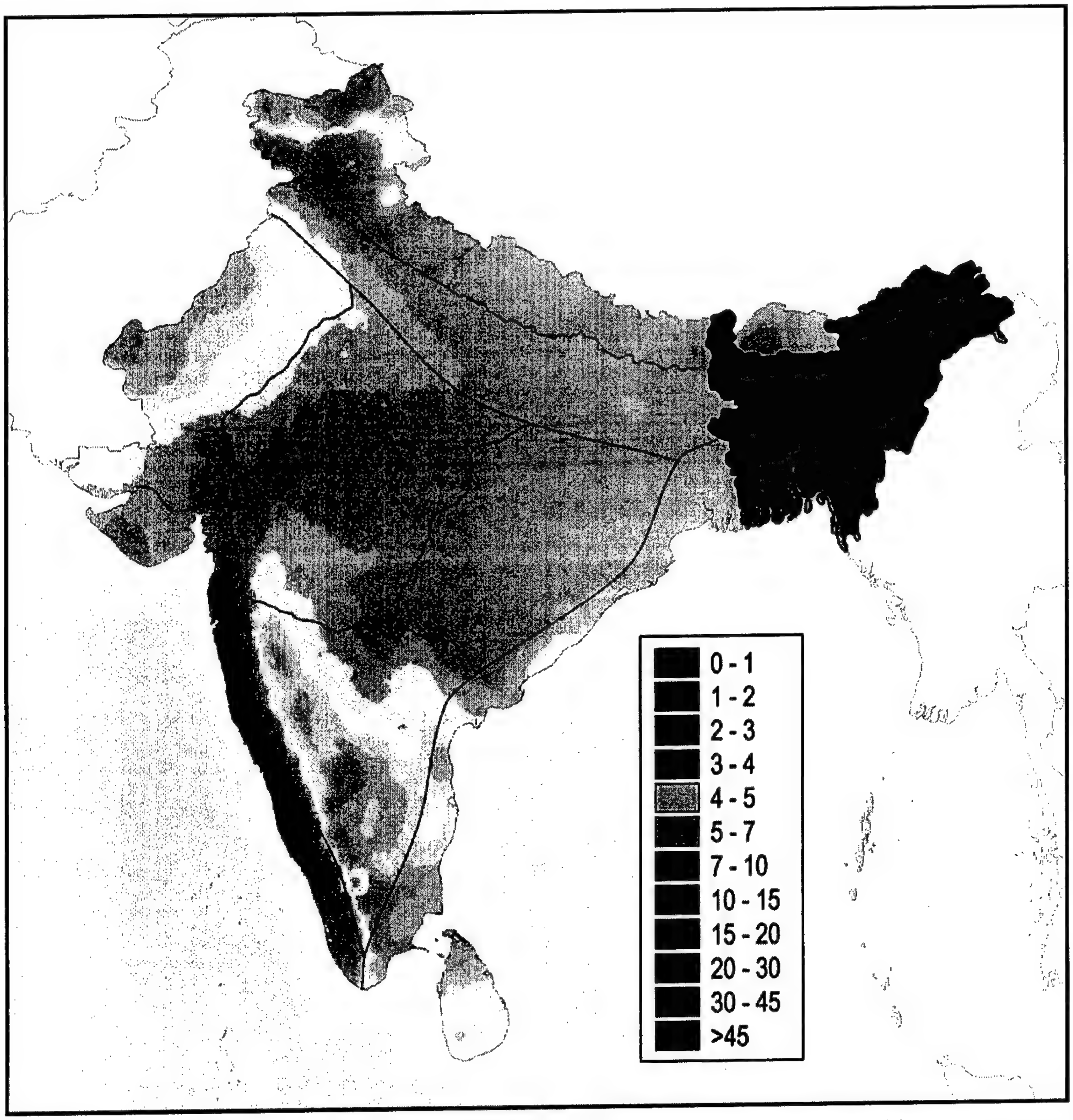


Figure 3-23. July Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

The variance is caused by terrain. In the northeastern valleys, rainfall varies widely according to exposure to synoptic wind flow. Lee locations average 1-5 inches (25-127 mm) of rain in June, 10-15 inches (254-381 mm) in July and August, and 5-10 inches (127-254 mm) in September. Windward locations average 10-20 inches (254-508 mm) in June, 15-25 inches (381-635 mm) in July, 10-20 inches (254-508 mm) in August, and 5-15 inches (127-381 mm) in September. The amounts are highest closest to the Bay of Bengal. Figure 3-23 shows mean July precipitation amounts in various locations.

The monsoon rains vary widely. The rains may arrive late, there may be long monsoon breaks or more breaks than normal, or the rains may last longer than usual or be more concentrated in one area than usual. In any given southwest monsoon season, it is likely one area will have drought while another in the same larger region is flooded. Rain falls frequently, although not every day everywhere. Rain falls most in the Khasi Hills and in the eastern highlands on the windward slopes, an average of 12-20 days in June, 20-25 days in July, 15-22 days in August, and 12-18 days in September. Elsewhere, rain falls 5-15 days in June, 15-22 days in July, 10-20 days in August, and 5-15 days in September. Leeward sites have the fewest days with rain and the lowest rain amounts. Thunderstorms are most common in the Bengal basin and on the windward slopes of the Khasi Hills. Thunderstorms occur an average of 5-10 days in June, 2-7 days in July, 3-5 days in August, and 3-9 days in September (see Figure 3-24).

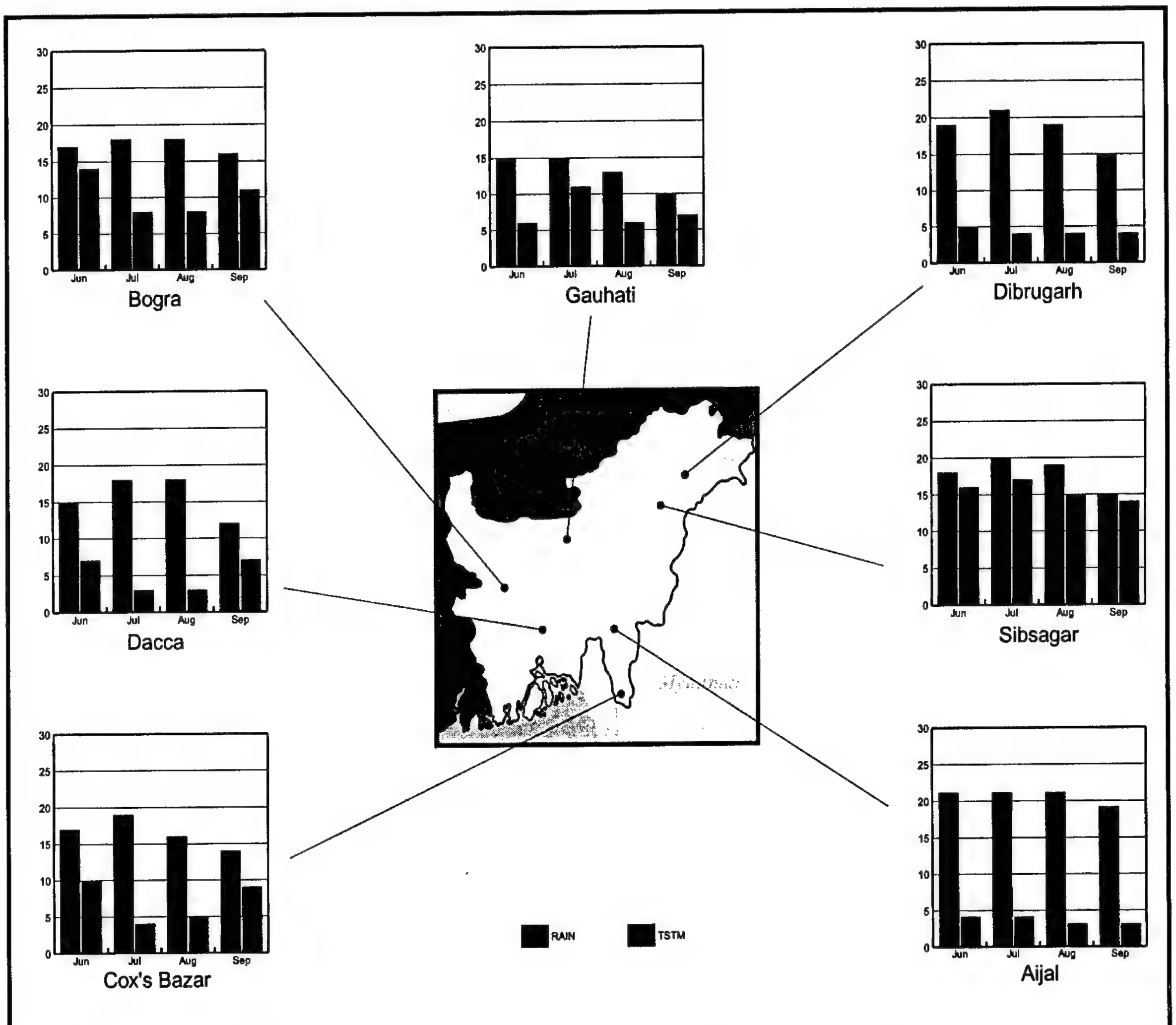


Figure 3-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The thick clouds and rains cool temperatures somewhat, however, the relative humidity rises dramatically. In general, the higher the moisture content of the air, the narrower the diurnal temperature range. The October mean highs are 87° to 91°F (31° to 33°C) in the lowlands and 77° to 82°F (25° to 28°C) in the leeward highlands. At windward sites, the range is 72° to 77°F (22° to 25°C). See Figure 3-25. On average, the mean highs are 3 Fahrenheit (1.5 Celsius) degrees cooler per 1,000 feet of elevation, and cloud cover lowers that even more, as much as another 6 Fahrenheit (2-3 Celsius) degrees. October mean lows are 68° to 74°F (20° to 23°C) in the lowlands, 55° to 62°F (13° to 17°C) in the leeward highlands, and 63° to 67°F (17° to 19°C)

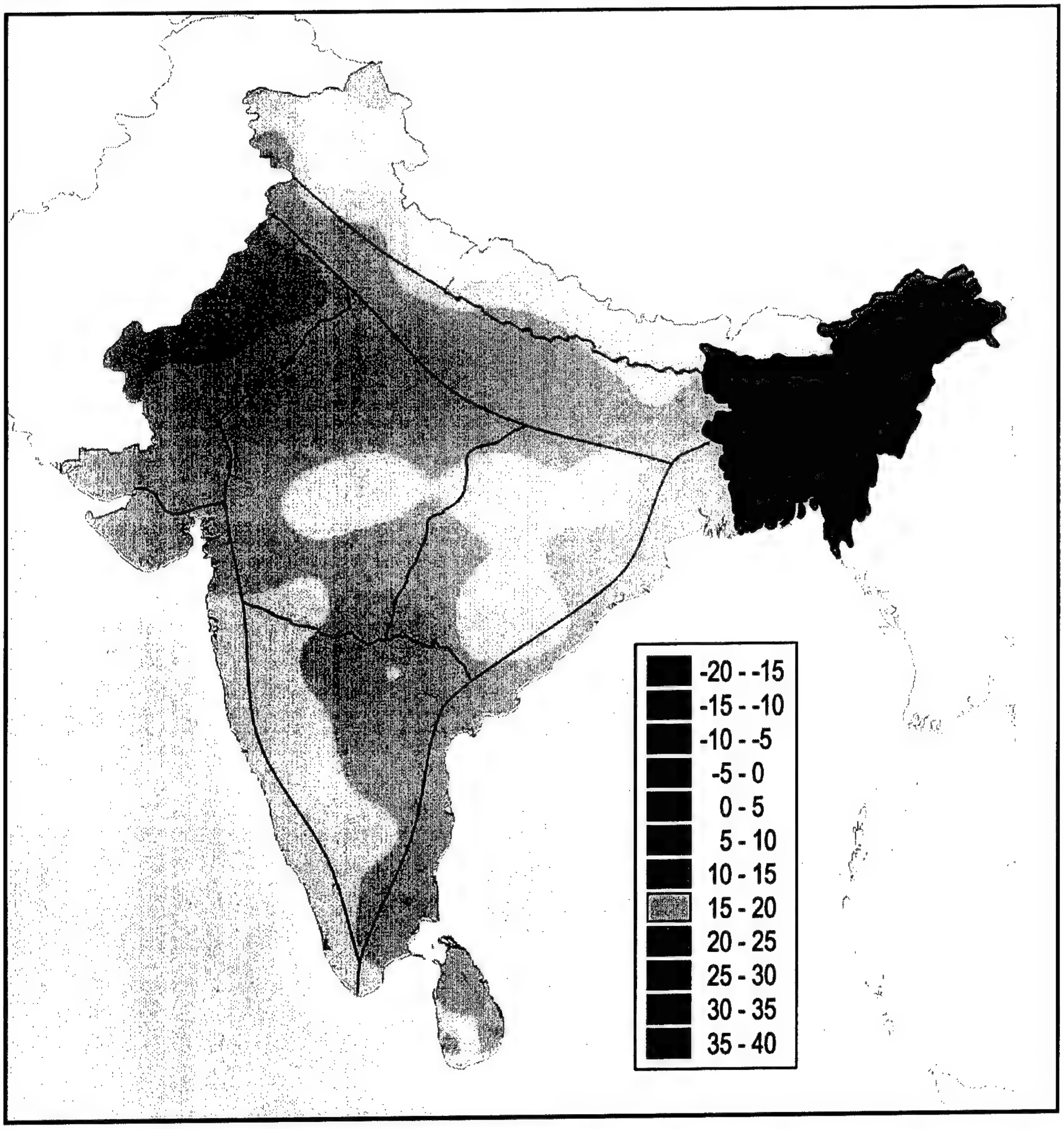


Figure 3-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

in windward sites (see Figure 3-26). By November, mean highs are 79° to 85°F (26° to 29°C) in the lowlands, 73° to 78°F (23° to 26°C) at leeward highlands, and 68° to 72°F (20° to 22°C) at windward highlands. Mean lows are 62° to 67°F (17° to 19°C) in the lowlands, 58° to 62°F (14° to 17°C) in the windward highlands, and 45° to 50°F (7° to 10°C) in the leeward highlands. Extreme highs in October are 100° to 104°F (38° to 40°C) and in November, they are 94° to 97°F (34° to 36°C). Extreme lows are 48° to 51°F (9° to 11°C) in October and 34° to 38°F (1° to 3°C) in November.

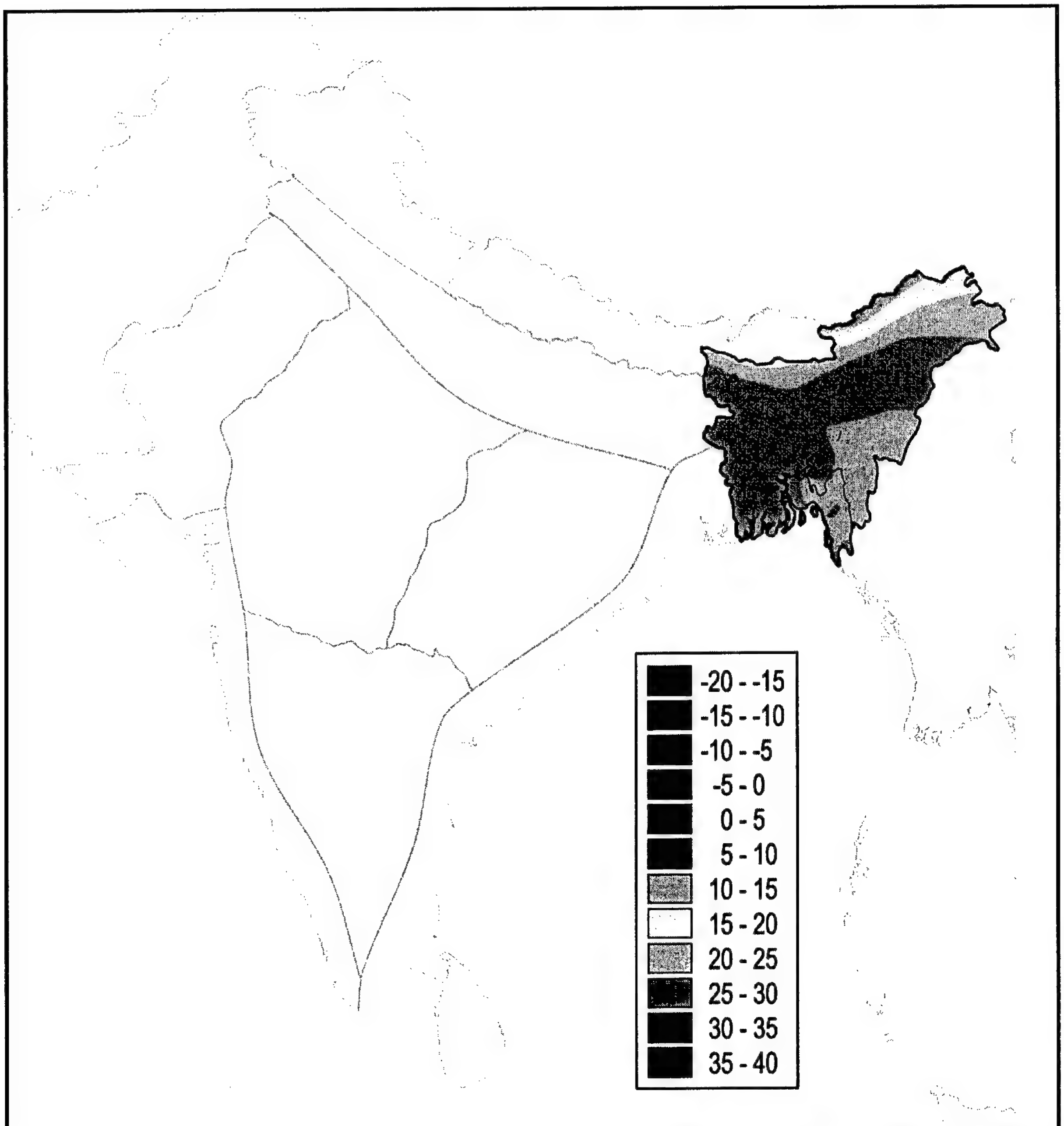


Figure 3-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. The rains of the southwest monsoon season end. The equatorial trough (ET) begins its retreat southward in this period as the Asiatic low fades away. The withdrawal of the southwest monsoon occurs first in the northernmost part of the region; the ET is out of northern India by mid-October. Heavy rains accompany the ET as it moves through an area.

The equatorial westerlies, the Somali jet, and the TEJ all disappear. The deep band of easterlies also retreats southward in this phase. By the end of November, it will be largely south of the peninsula. The Asiatic high begins to form now as well, and wind flow at all levels is relatively ambiguous. Because shear aloft is reduced in this transition season, this is when tropical cyclones have the best chance of growing powerful. The Bay of Bengal is a favored breeding ground for tropical cyclones. October and November have more cyclonic storms develop into tropical cyclones than any other period of the year. These storms are not as powerful as open water storms can be, but they still carry heavy rains and strong winds to the coasts.

Generalized northeasterly flow is established by the end of November, and the induced lee-side trough at the southern foot of the Himalayas starts to develop. This will provide a track for migratory lows out of Europe. Once the STJ is south of the mountains, lows will move through very quickly. Early season lows are not uncommon by mid-November.

Sky,Cover. Clouds are similar to the southwest monsoon types until the ET has retreated south from a particular place; cloud cover becomes winter-like. Cloud cover decreases significantly over this season. For most of the period, the skies are clear or scattered over most of the area. Diurnal changes in cover varies. Except for the coast and in river valleys, cloudiness is slightly greater in the afternoon. There is a rapid decrease in low cloudiness behind the southwest monsoon.

October ceilings below 5,000 feet occur 5-10 percent of the time in most lowland sites and 10-15 percent of the time on the coast (see Figure 3-27). In the highlands, they occur 25-35 percent of the time in the morning and 15-25 percent of the time the rest of the day. In windward locations in the Brahmaputra River valley, such as Sibsagar, they occur 55-65 percent of the time in the morning and 35-45 percent of the time the rest of the day. Imphal has similar rates, 55 percent of the time in the mornings and 25 percent of the time after noon. By November, all occurrences of ceilings below 5,000 feet are lower. Most places in the lowlands and coast have them 5 percent of the time or less in the morning and rarely after that. In the highlands, they occur 20-30 percent of the time in the mornings and under 5 percent of the time the rest of the day. In windward Brahmaputra River valley locations, they occur 35-45 percent of the time in the morning and 15-25 percent of the time the rest of the day. Imphal drops to 30 percent of the time in the mornings and 5 percent of the time the rest of the day.

Ceilings below 1,000 feet occur rarely in the lowlands and under 5 percent of the time in most highland locations. Imphal is an exception--it gets them 40 percent of the time in October mornings and 25 percent of November mornings. Ceilings lift off by mid-morning and occur 10-15 percent of the time the rest of the day. Windward Brahmaputra River valley sites get ceilings below 1,000 feet 30-35 percent of the time in both October and November mornings and 30 percent of the time in October and 10 percent of the time in November the rest of the day.

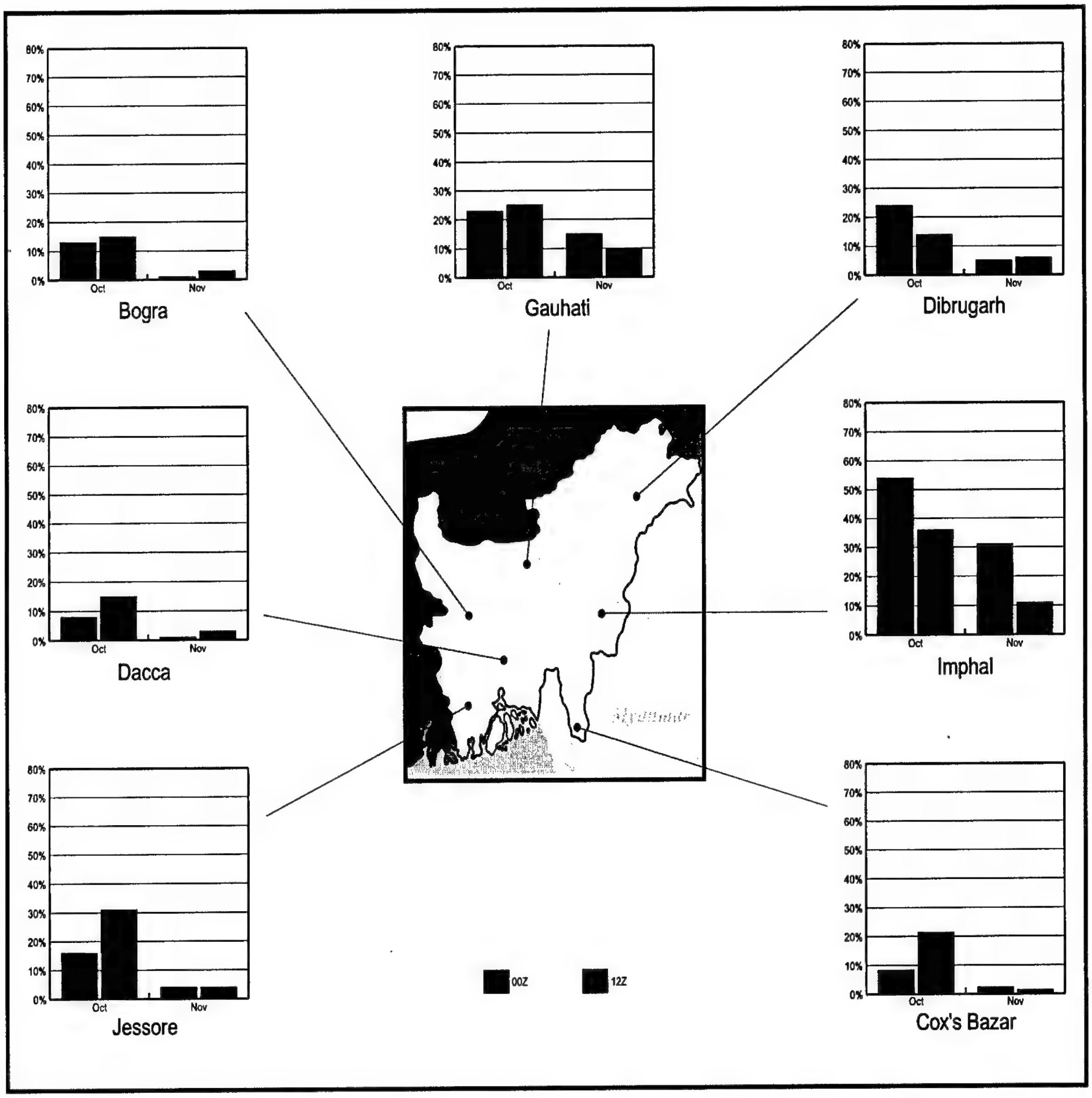


Figure 3-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Early morning fog dissipates before mid-morning. Valley fog forms in the mornings but is still quite shallow as inversions are not yet strong. Rain restricts visibility before mid-October then drops off dramatically. Hill stations report fog all year, but as cloud cover falls away with the monsoon, the frequency of occurrence also falls.

Visibility below 2 1/2 miles (4,000 meters) occurs under 5 percent of the time in most lowland areas in the evening, night and morning hours. Visibility lowers over the course of the day in haze and dust. Large urban centers, such as Dacca, typically have visibility below 4,000 meters 10 percent of the afternoons in October and 20 percent of the afternoons in November because of air pollution.

In some windward highland areas and in windward Brahmaputra River valley locations, visibility below 4,000 meters occurs 10-15 percent of the time all day in October and 25-35 percent of the time in the morning and 10-15 percent of the afternoons in November. Figure 3-28 shows the seasonal percent frequency of below 4,000 meters across the region.

Visibility below 1 1/4 miles (2,000 meters) almost never occurs in most places in this region. In highland windward locations and in windward Brahmaputra River valley locations, visibility below 2,000 meters occurs 5 percent of the time in October mornings and 20 percent of the time in November mornings. It rarely occurs the rest of the day.

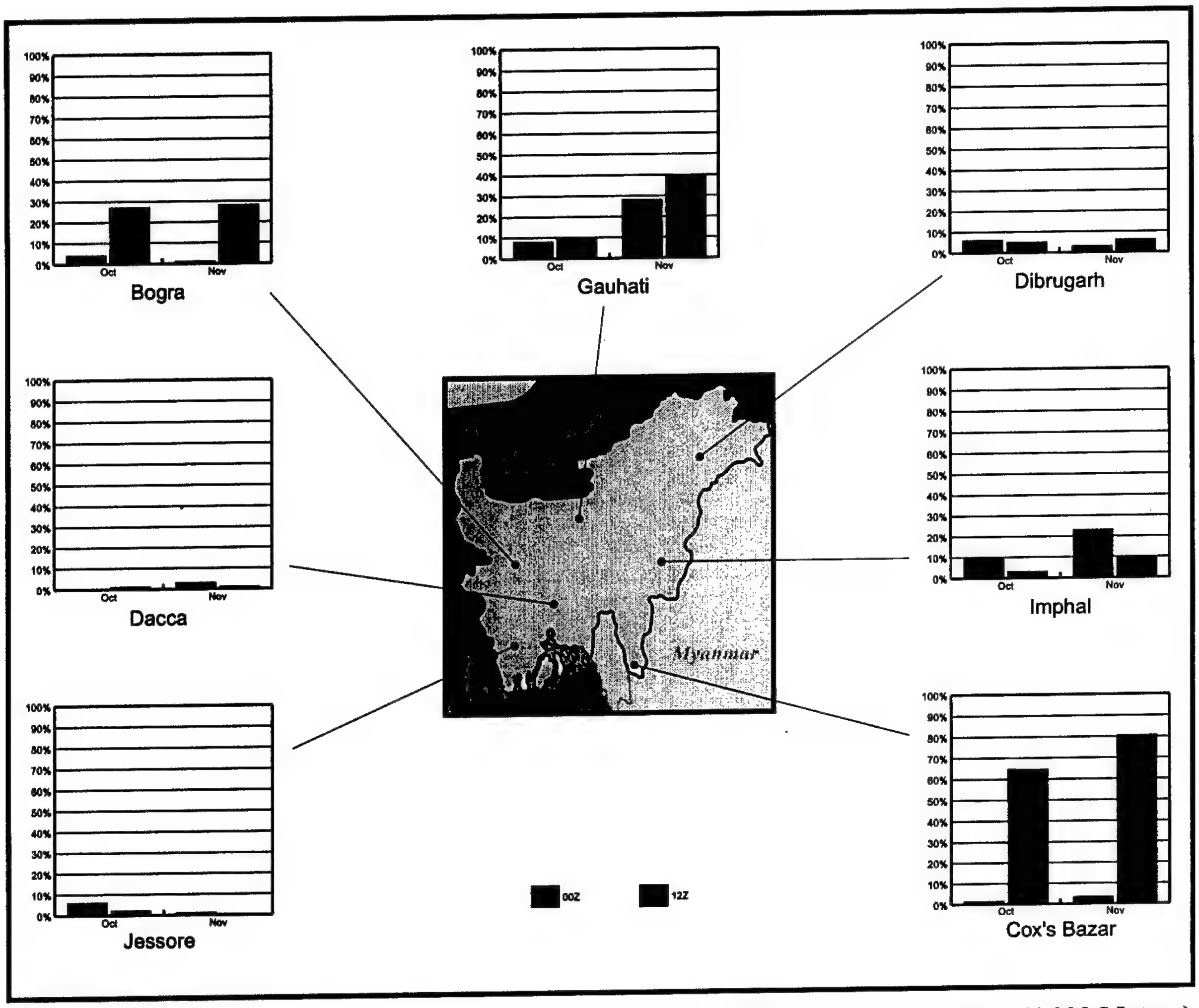


Figure 3-28. Post-Monsoon Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. As they do the rest of the year, the winds in the Brahmaputra River valley flow from the northeast at 5-10 knots (see Figure 3-29). In the rest of the region, local influences play a larger role than synoptic flow as the season transitions from southwest to northeast monsoon. In the Bengal plain, the strong sea breeze of the southwest monsoon abates and prevailing winds are generally under 5 knots except on the coast, where sea breeze winds can rise to 10-15 knots on a clear day.

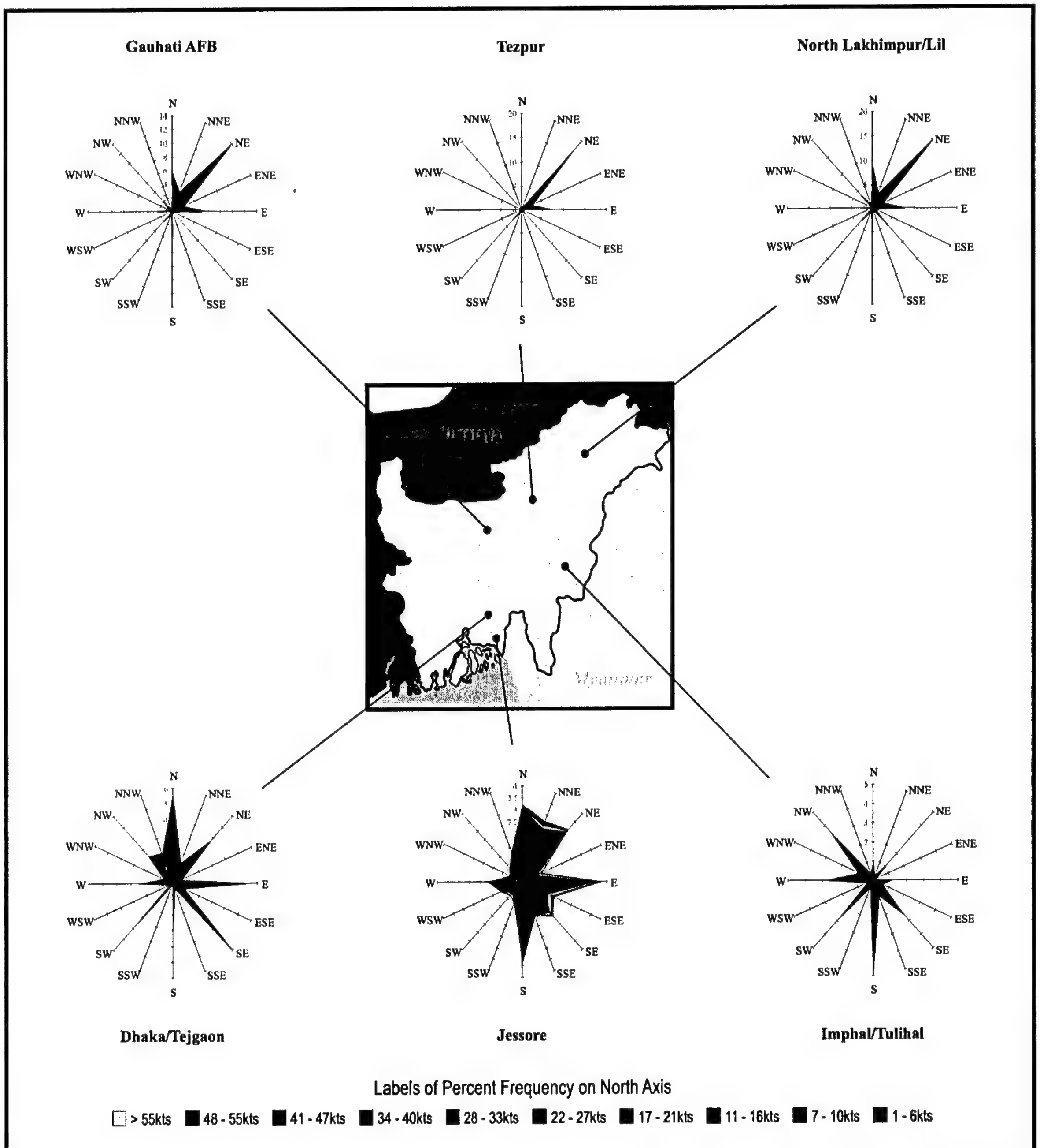


Figure 3-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The winds at 850 mb are from the northwest at 10 knots in both months. The 700-mb winds hold from the northwest at 10 knots. At 500 mb, the westerly winds start in October at 15 knots; by November, they rise to 30 knots. At 300 mb, westerly winds at 25 knots in October rise to 60 knots by November. See Figure 3-30 for October upper-wind roses over Dacca.

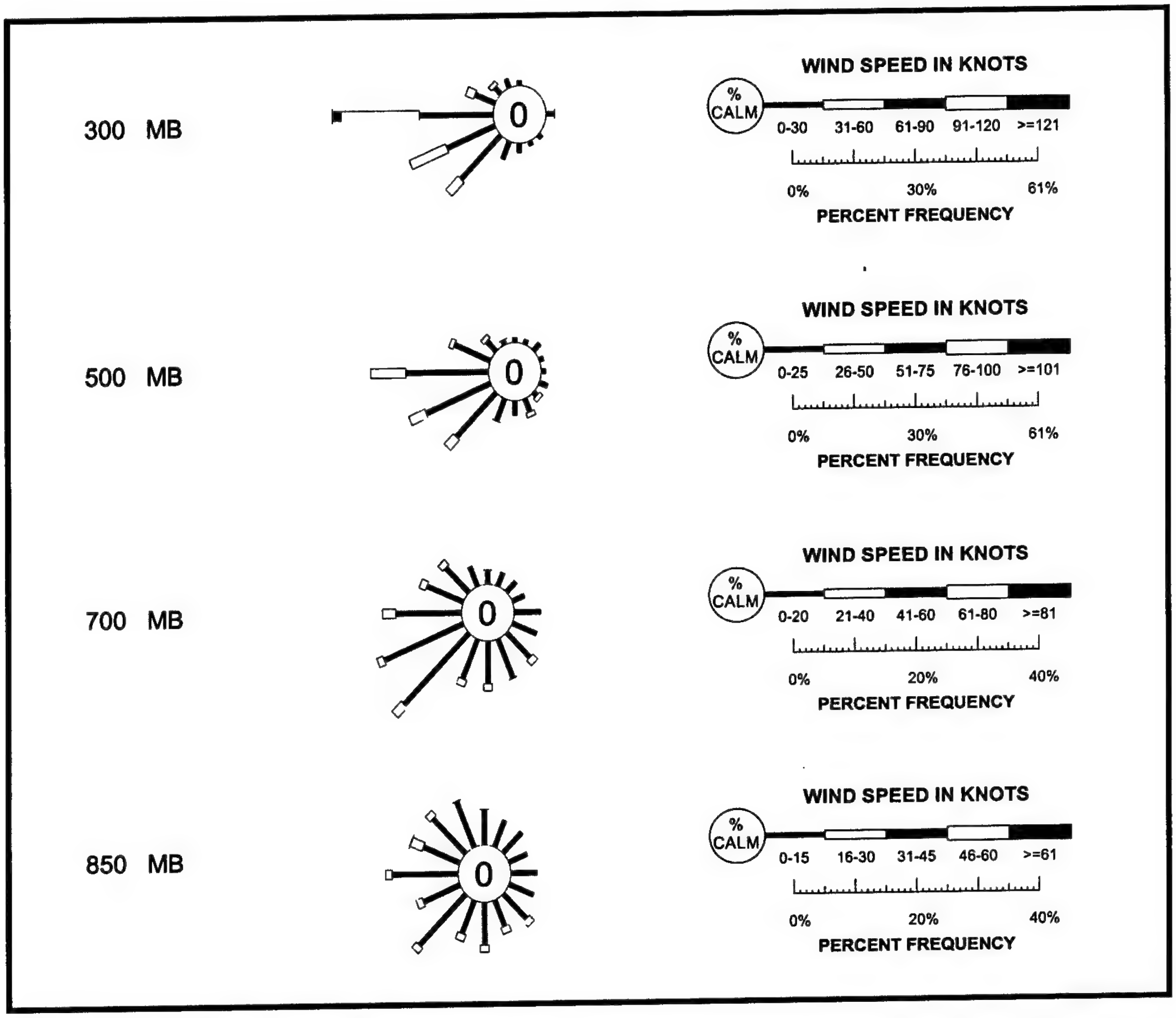


Figure 3-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Dacca.

Precipitation. Behind the southwest monsoon, dry weather prevails over the entire area. Only the eastern highlands and near the mouth of the Ganges River get 1-2 inches (25-51 mm) of rain in November. The rest of the area is below one inch (25 mm). In October, rain falls an average of 7-10 days in windward locations in the eastern highlands and 1-4 days in leeward sites. By November, no location has more than 3 rain days; most places have one day or less with rain. See Figures 3-31 and 3-32 for October mean precipitation amounts and seasonal thunderstorm and rain days, respectively.

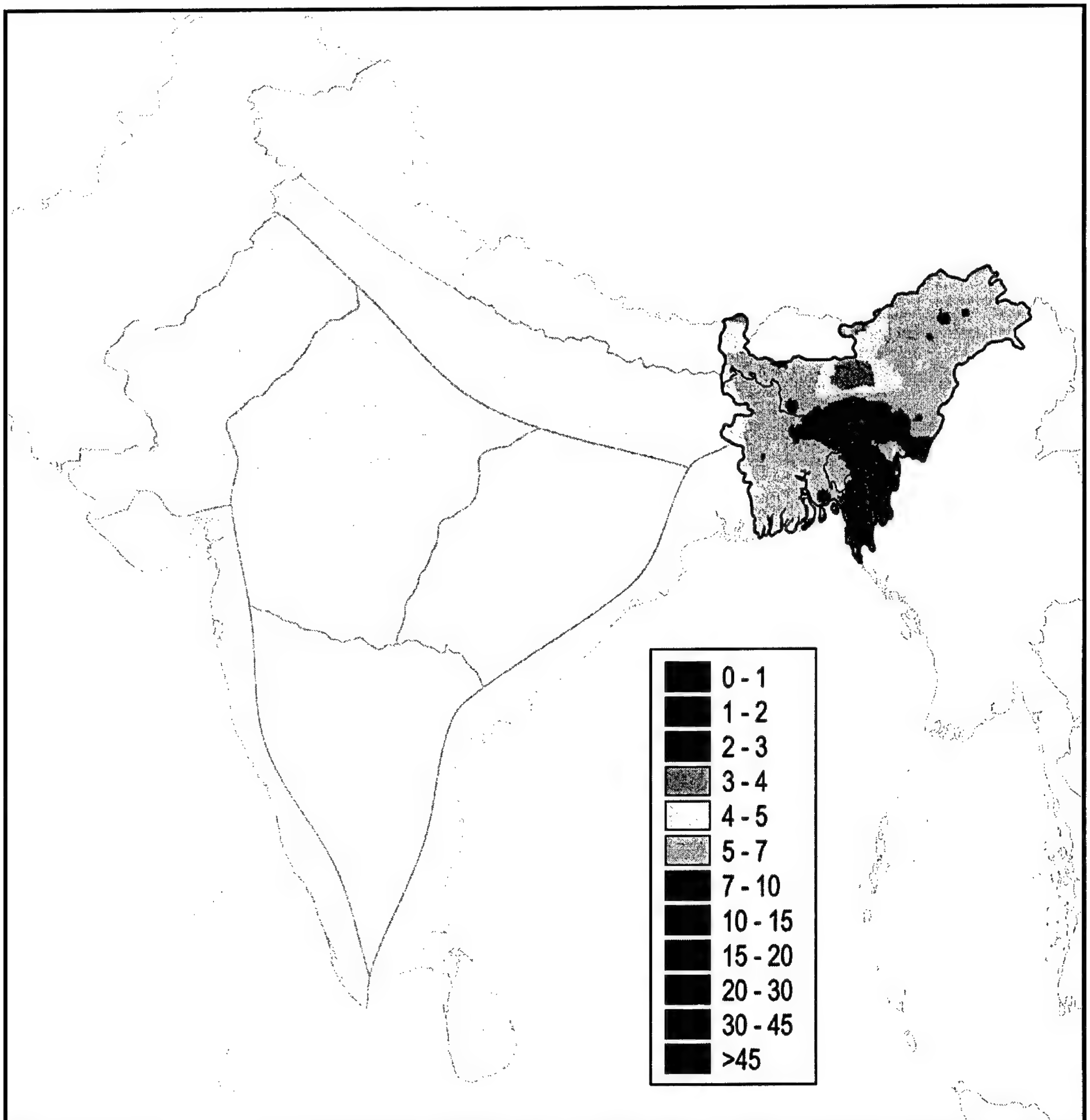


Figure 3-31. October Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

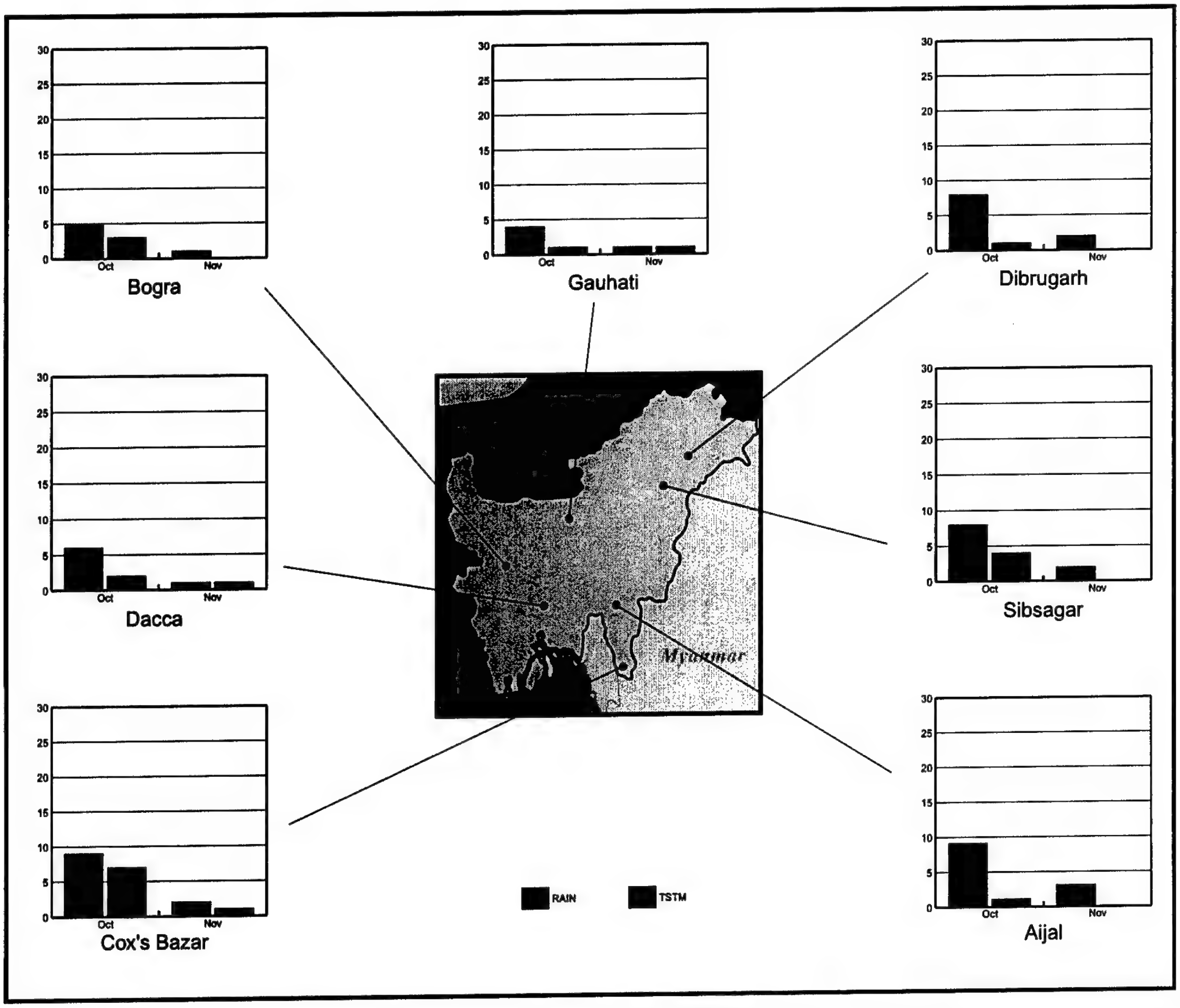


Figure 3-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures rise briefly before cooling to the winter averages. The range of temperatures is smallest in Bangladesh, especially on the coast and in the eastern highlands. The October mean highs are 87° to 93°F in the lowlands, 80° to 84°F in the leeward highlands and 71° to 77°F in the windward highlands under cloud cover. By November, the mean highs in the lowlands cool to 79° to 84°F. The leeward highland mean highs are 73° to 78°F and the windward highland mean highs are 66° to 73°F. The October mean lows are 73° to 80°F in the lowlands, 67° to 73°F in the windward highlands and 55° to 65°F in the leeward highlands. In November, they cool to 58° to 65°F in the lowlands, 52° to 58°F in the windward highlands, and 45° to 52°F in the leeward highlands. Figure 3-33 and 3-34 show the respective mean maximum and minimum temperatures for October.

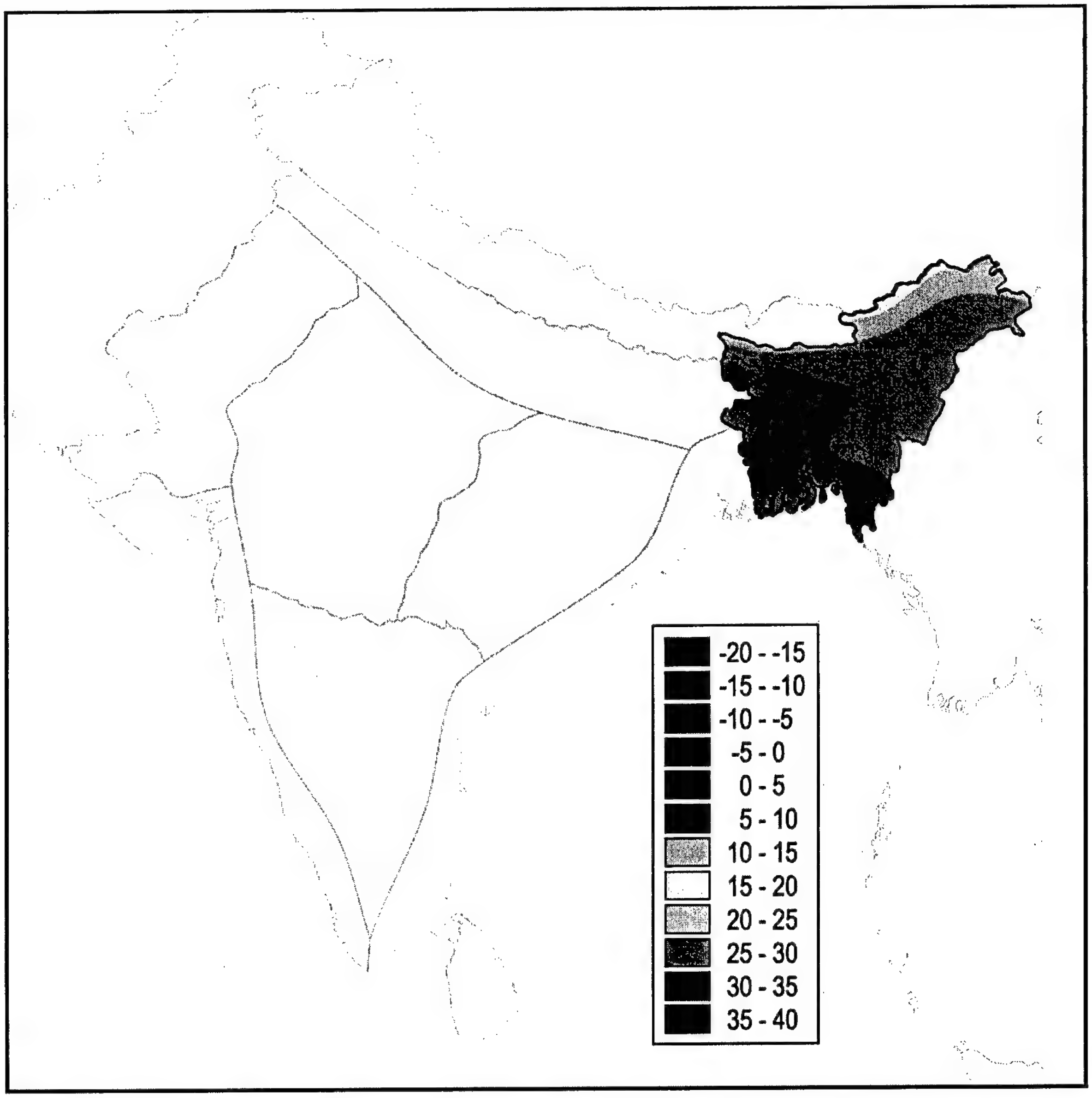


Figure 3-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures may be lower in November.

Extreme highs in October are 98° to 104°F. By November, they are 90° to 97°F. The highest temperatures occur in the inland lowlands. Extreme lows in October are 50° to 58°F in the lowlands and 41° to 50°F in the highlands. By November, they are 44° to 48°F in the lowlands and 34° to 39°F in the highlands. The lowest temperatures occur in the leeward mountain areas.

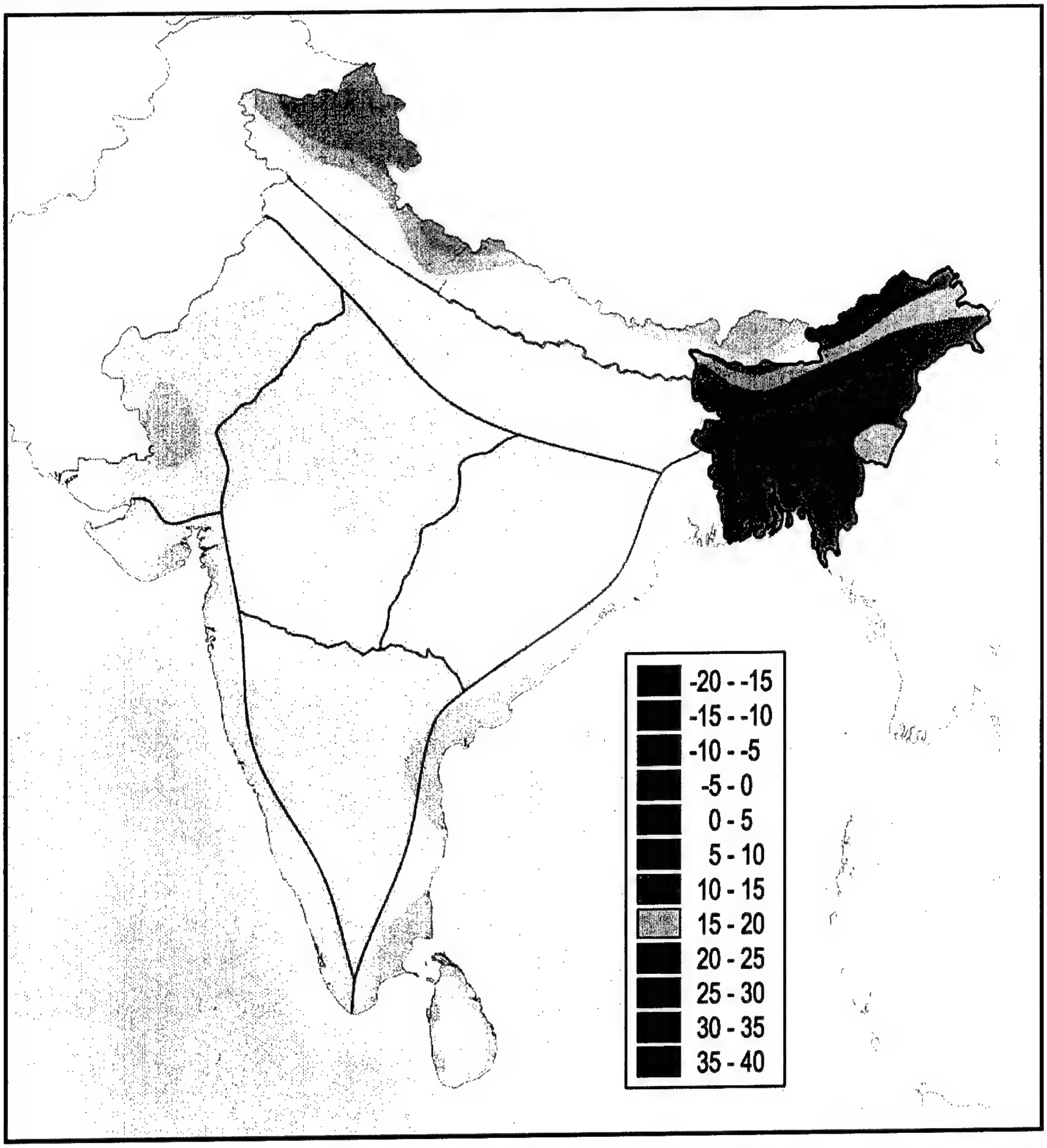


Figure 3-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures may be lower in November.

Chapter 4

CHOTA NAGPUR PLATEAU

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for the Chota Nagpur Plateau region.

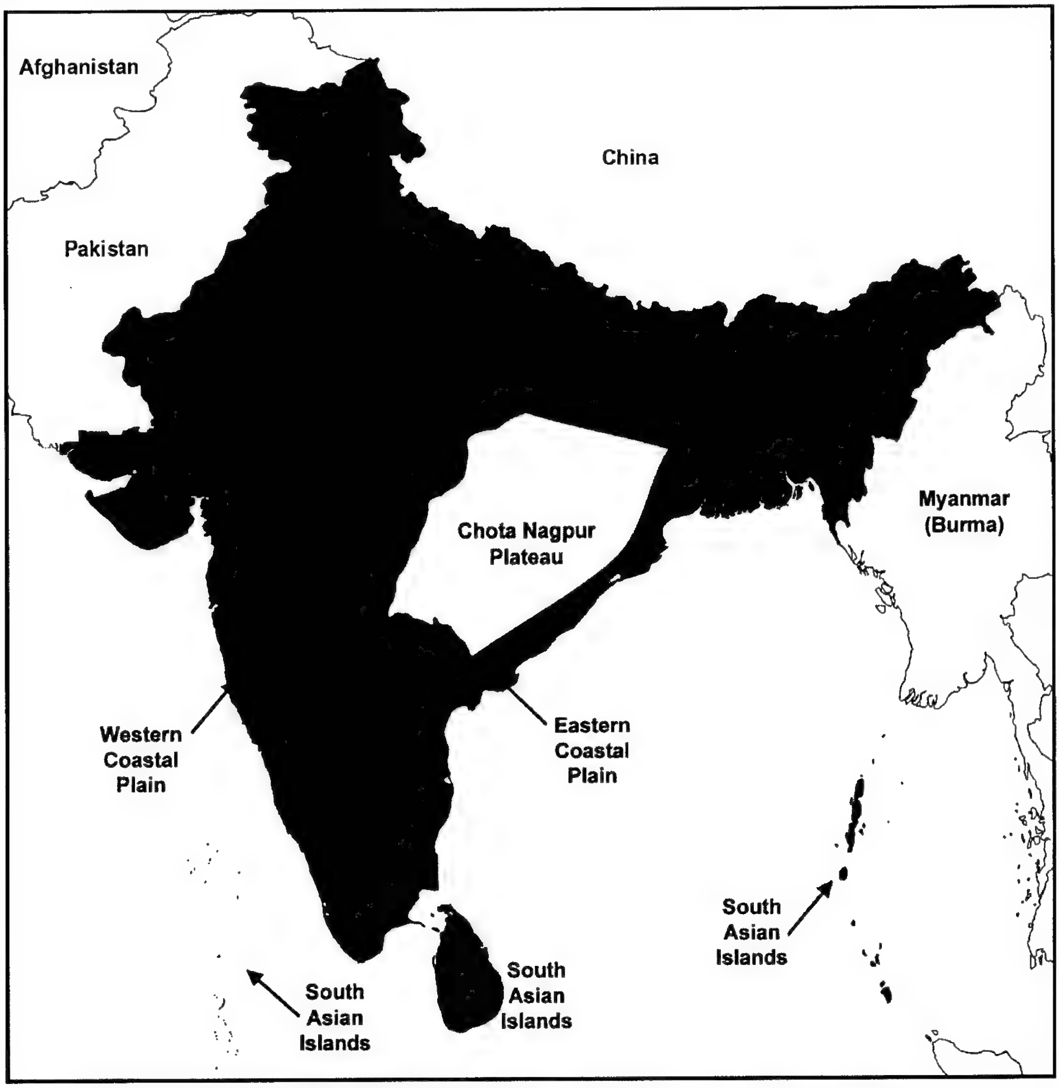


Figure 4-1. Chota Nagpur Plateau. The area in yellow depicts the Chota Nagpur Plateau in relation to the other South Asia regions.

List of Figures

Topography

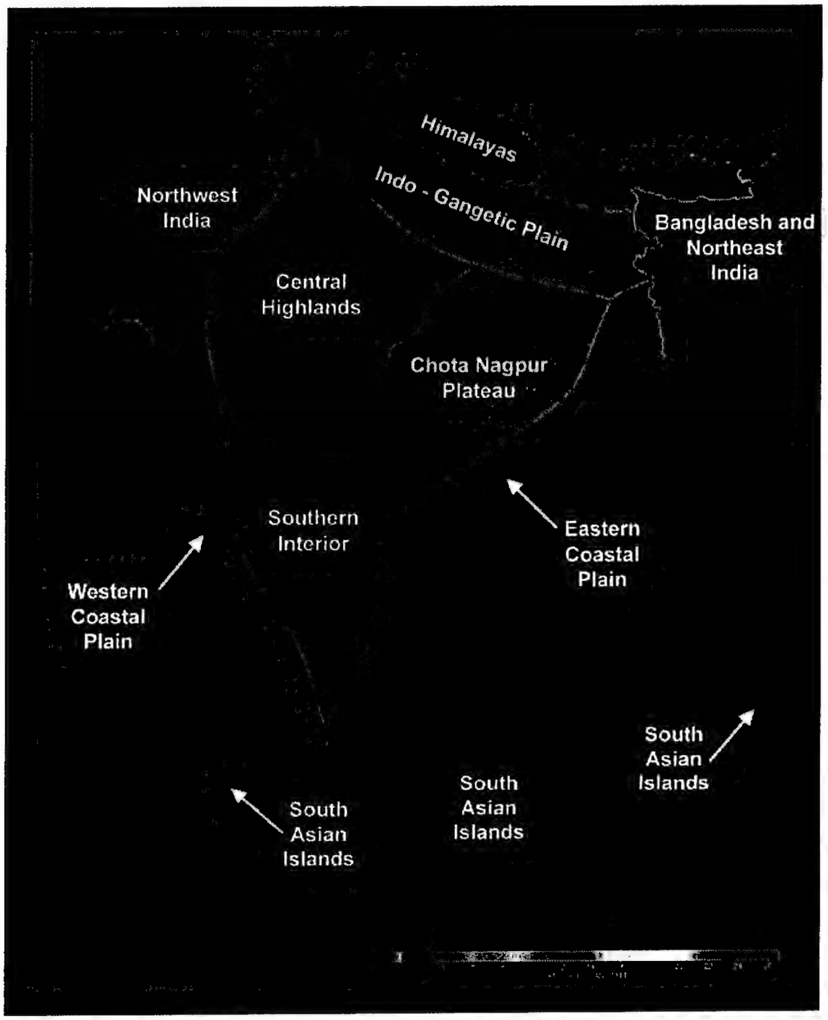


Figure 4-2a. Topography of the Chota Nagpur Plateau.

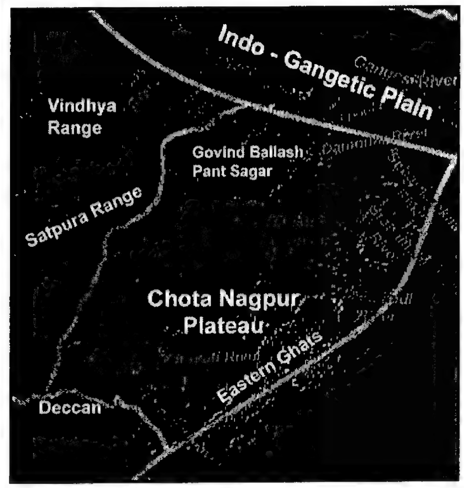


Figure 4-2b. Expanded View of the Topography of the Chota Nagpur Plateau.

Topography

Boundaries. This region includes the Chota Nagpur plateau from the southern boundary of the Indo-Gangetic plain in the north to the Godavari River in the south. The Eastern Ghats, included in the area, are the eastern edge of the region, and the western edge is marked by the Pranhita, Walinganga, Narmada, and Son Rivers. These rivers flow along the western rim of the plateau.

Mountains. The Chota Nagpur Plateau is latticed with numerous rivers that drain to the east coast, the central lowlands to the west and south, or the Indo-Gangetic basin to the north. The mean elevation of the plateau highland is 1,700-2,700 feet (500-800 meters) with small areas above 3,000-3,600 feet (900-1,100 meters) sprinkled throughout the region, mostly in the northern half. The lowlands average 700-1,000 feet (200-300 meters). Maximum elevations are in the Eastern Ghats. There, the elevations range from 3,500-4,500 feet (1,000-1,400 meters) with peaks of 5,200- 5,500 feet (1,600-1,700 meters) between 17.5° and 18.5° N.

Major Water Bodies. Although this interior region does not abut any major waters, the Arabian Sea and the Bay of Bengal both play significant roles in the weather. Indirectly, the Indian Ocean is also significant.

Lakes. There are numerous small, natural lakes on the plateau, but most large lakes are man-made. Hirakud Reservoir is the largest in the region. Fed by several rivers, the reservoir is dammed at the southeastern corner at Sambalpur. Govind Ballash Pant Sagar is another large reservoir on a tributary of the Son River in the north part of the region. Two smaller reservoirs lie between the western-most ridge of the Eastern Ghats

and the main range. Balimila Reservoir, is the southern one of the two and the larger of the two; both are fed by run-off from the higher peaks to the east.

Rivers. From north to south, the major rivers are the Son, the Damodar, the Brahmani, the Mahanadi, the Godavari, the Wainganga, and the Narmada. Although many rivers lace the plateau, most are tributaries to these larger rivers. Rivers flow from the plateau in all directions. The Son flows north to the Ganges, the Damodar, Brahmani, Mahanadi, Walinganga, and Godavari all flow to the Bay of Bengal, and the Narmada flows west to the Arabian Sea.

Major Climatic Controls

Asiatic High. This thermal high develops over Asia and dominates the weather over the entire continent from November to April. The vast pool of cold, dry air it pushes outward in all directions is a key part of the northeast monsoon in south Asia. Because of the continental source of the air, the weather is dry. The leeside trough on the southern side of the Himalayas created by flow out of this high provides a track for storms that move out of Europe on the subtropical jet.

Australian High. This thermal high sets up over Australia during the Southern hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season in south Asia. This is the rainy season for south Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. This high does two different things. What it does depends on its strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe, which use the subtropical jet to zip through the region. When the Indian high is weak it enhances western disturbances.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in the Northern Hemisphere summer (May through October) and east and south in the winter (November to April). The high is linked to the position of the ET, which, in turn, marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south with the sun. At its strongest during the Southern hemisphere winter, it provides cross-equatorial flow from May to October (reflected in both the Somali jet and the equatorial westerlies). This warm, moist flow contributes significantly to the ET shift to the north, and the onset of the southwest monsoon.

Asiatic Low. This is a thermal low that replaces the Asiatic high during the Northern hemisphere summer. The land heats, and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This is a thermal low that develops over Australia during the Southern hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the area of the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has a distinct rainy season and dry season. Under the northeast monsoon,

the region is largely dry. Under the southwest monsoon, it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid-May and late June. Duration of the rainy season also varies widely. In the north, the southwest monsoon season is short; in the southern end of the peninsula, it is often twice as long as in the far north.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough or near-equatorial trough, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north, the southwest monsoon dominates in South Asia. When it shifts south, the northeast monsoon assumes control.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclonic storm systems that affect this region. Most of the rainfall in this area occurs from storms that develop or refire over this body of water along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active time is in October and November with a secondary maximum in April and May. Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season. An upper-level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet. Also known as the east African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. This jet moves 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa. The western edge of the outflow air mass piles up against the eastern slopes of the high mountains of the eastern African coast. This result s in a terrain-induced zone of tight pressure gradient, and the jet develops there. The Somali jet is a key element in formation of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the Northern Hemisphere. The air mass recurves eastward and these westerly winds take over.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season (November to April) when its southern branch slips south of the Himalayas. Low pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. During the southwest monsoon, the STJ is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter (November through April), several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move theses waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere mid-latitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also,

since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought.

Easterlies. This deep east wind band persists year round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Easterly Waves. During the southwest monsoon season, easterly waves help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over Sri Lanka and the southern tip of the peninsula. The intensity and frequency of easterly waves are indicators of the strength of the monsoon.

Cyclonic Storms. Monsoon depressions, tropical cyclones, tropical waves, tropical vortices, mesoscale convective complexes, and cloud clusters are all types of cyclonic storms of varying scales of intensity and size. Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Some travel into the area from the west (western disturbances). Some of these factors have influence during the southwest monsoon season, such as the Tibetan anticyclone, easterly waves and the India-Myanmar trough. The ET influences the weather during the transition periods when it moves through the area. During the northeast monsoon, western disturbances and tropical vortices are the bigger players in the development of weather systems. Regardless of when they develop, some storms can be fierce. Because the waters of the bay are so confined, however, storms do not have the opportunity to develop the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms tend to come ashore on the peninsular east coast of India then recurve northward. The heaviest precipitation falls in the southwest through south quadrants of the storms.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to monsoon rainfall. During the southwest monsoon season, these storms move along the ET toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of upper-level low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in South Asia are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the large scale flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Off shore winds clear the skies over land by pushing cloud cover out to sea. These same winds can slide convection that developed over the mountains down into the lowlands between them and the sea. Depending on the steepness of the slopes, the downslope flow can create a "front" that fires thunderstorm activity all along the convergence zone between the cool mountain air and the warmer, moist air of the sea. This makes up a line of thunderstorms that marches to the sea over the lowlands.

Hazards for All Seasons

Turbulence. In winter and the hot season, convective turbulence may reach 10,000 feet. The turbulence is usually light-moderate but can reach the severe category. Mechanical turbulence downwind of the Western Ghats may occur up to 50 miles (80 km) downwind. The turbulence is usually moderate but may reach the severe category. Obscured by the heavy clouds of the southwest monsoon, rotor clouds will not be visible. Moderate to severe turbulence will be encountered in the vicinity of the subtropical jet at 35,000-40,000 feet during the winter and hot seasons. During the southwest monsoon, moderate to severe turbulence occurs near the tropical easterly jet at 40,000-45,000 feet.

Aircraft Icing. The mean height of the freezing level is 16,000-18,000 feet all year. The mean height of the -20° C isotherm is 26,000-28,000 feet. Above and below these levels, icing does not usually occur. During the winter and hot season, there is little threat from icing. Heavy, dense clouds blanket the area during the southwest monsoon. In clouds, icing could occur between 16,000-28,000 feet.

Tropical Cyclones. Bay of Bengal storms occasionally move across peninsular India and bring heavy, layeredclouds and torrential rains. Two tracks are common. One takes storms to landfalls in the northwestern corner of the bay. The other, the more favored of the two, takes them across the southern third of the peninsula. While coastal areas are most vulnerable to the full range of destruction a storm brings, inland areas are also subject to flooding and high winds.

Thunderstorms. Thunderstorms occur most in May-June and September-October, during the ET advance and retreat. Thunderstorms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does it is usually small, soft, and causes little damage.

Flooding. Incredible amounts of rain fall in a very short period of time during the southwest monsoon. Streams and rivers overflow their banks and fill the valleys. Flash floods occur with little or no warning.

Winter

General Weather. In winter, the northeast monsoon dominates. The massive thermal high over Asia drives the ET south of the equator. The thermal low over Australia helps pull it south. This is a dry season influenced by migratory lows from Europe. These western disturbances bring cloudiness and rain to northern India. The subtropical jet shifts south of the Himalayan massif and pushes these lows along the induced leeside trough at the southern foot of the mountains. The moisture retained after the long trip from Europe is joined by a little moisture from first the Arabian Sea, then the Bay of Bengal as the lows zip through northern India. These migratory lows keep northern India cooler and more cloudy than would be expected for mostly offshore flow. The storm track along the foot of the Himalayas exists from December to March and is at its southern-most position at the end of the season. It vanishes by late March. The deep band of easterlies that dominate upper-air flow in the southwest monsoon are held south of 5° N and westerlies that take over in this season.

Onset of the northeast monsoon, or winter, season is at a different time within a general frame that depends on latitude and terrain. The ET retreat southward marks the onset on the season. Obviously, it occurs first in the north and last at the south end of the peninsula. Usually, the ET has moved south of the Godavari River by the end of October. The northeast monsoon brings northerly winds to the region.

Tropical cyclones and other cyclonic storms are less likely in this season than during the southwest monsoon, however, the storm season extends to November. The transition periods in October-November and in April-May, when the ET travels through the Bay of Bengal, is when the cyclonic storm occurrence rates peak. Although the rate drops off sharply after November, there is an incidence of at least once storm in every month of the year. The minimum number occurs in February, when the northeast monsoon is at its greatest strength.

Bay of Bengal cyclonic storms are fired by a number of triggers. They develop along the ET, at the southern edge of the Tibetan anticyclone, and along the India-Myanmar trough. Western disturbances, easterly waves, and vortices also grow into storms over the warm waters of the bay. While some of these factors have influence during the southwest monsoon season, such as easterly waves and the India-Myanmar trough, the early and late parts of the northeast monsoon season still experience weather stirred by them. Regardless of when they develop, the storms can be fierce. Because the waters of the bay are so confined, however, storms do not have the power of open ocean tropical cyclones. Still, they carry vast amounts of precipitation to the shores of India and Bangladesh, cause extensive flooding and loss of life, and destroy crops and property. Storms that develop in this season are most likely to strike the southern end of the peninsula.

Sky Cover. The weather is dominated by clear or scattered skies, however, western depressions cause some cloudiness in the northern areas in the latter part of the season. Average cloud cover varies only slightly from month to month, but local effects cause significant variation between locations. Most places have an average of 25-35 percent cloud cover. Diurnally, late afternoon has the greatest amount of cloud at higher elevations. At lower elevations, there is little variation. The least cloud cover occurs over night and into the early morning hours.

As seen in Figure 4-3, ceilings below 5,000 feet occur 3-5 percent of the time most of the day all winter. In the late afternoon, sites at higher elevations have them 10-15 percent of the time and stations at lower elevations have them 3-5 percent of the time. January has a slightly higher rate than the other months of winter; however, percentages are just at the high end of the same ranges. Ceilings below 1,000 feet rarely occur anywhere in the region in this season.

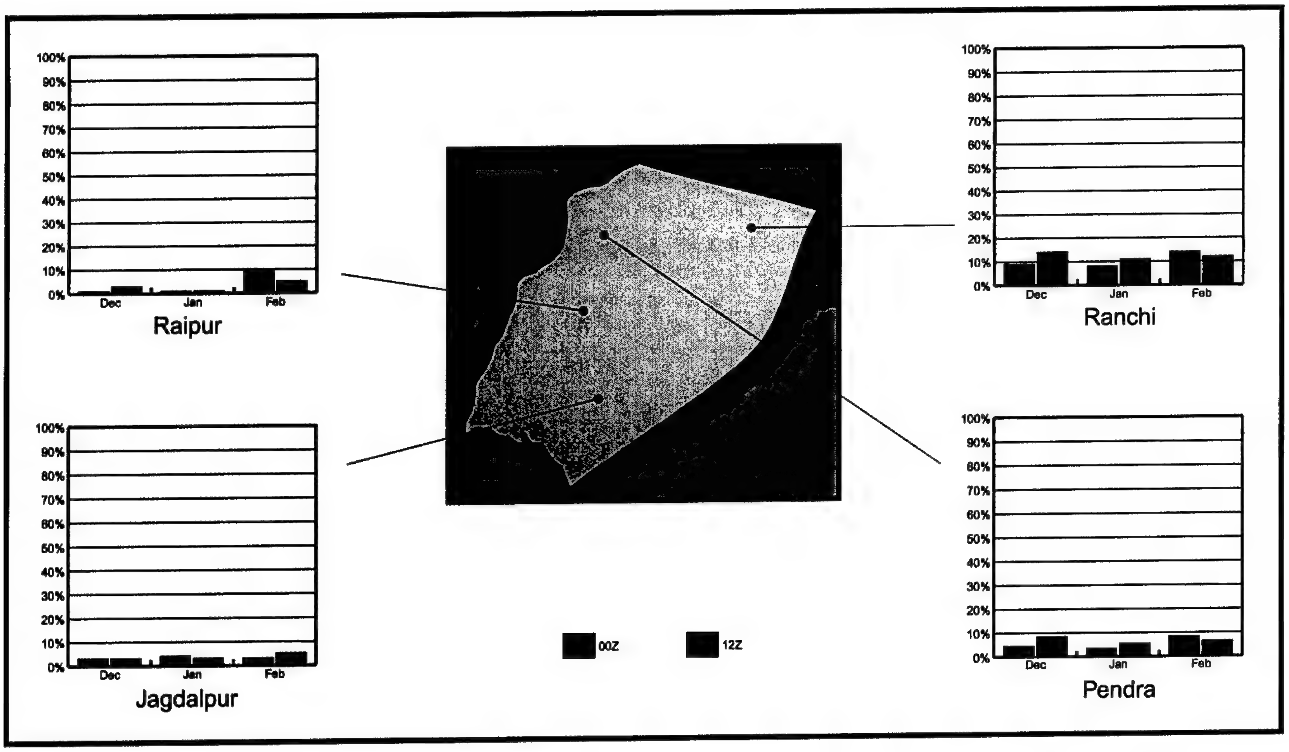


Figure 4-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility below 2 1/2 miles (4,000 meters) occurs in early morning fog, which dissipates shortly after sunrise. Places along river banks in the lowlands have the most fog and the most fog occurs in December and January. Places like Nagpur, by the Wainganga River, have visibility below 4,000 meters 15-20 percent of the time in the mornings and not at all the rest of the day. Everywhere else, fog occurs 4-8 percent of the time in the mornings and not at all the rest of the day. See Figure 4-4. Visibility below 1 1/4 mile (2,000 meters) occurs infrequently and is caused by fog in the mornings. Visibility below 2,000 meters occurs well under 5 percent of the time at sites along rivers in the lowlands and not at all everywhere else. The rest of the day, visibility below 2,000 meters does not occur.

By late in the season, dust causes low visibility in narrow zones around heavily trafficked areas of the interior as the soil dries out. In general, the best visibility of the day occurs in the afternoon.

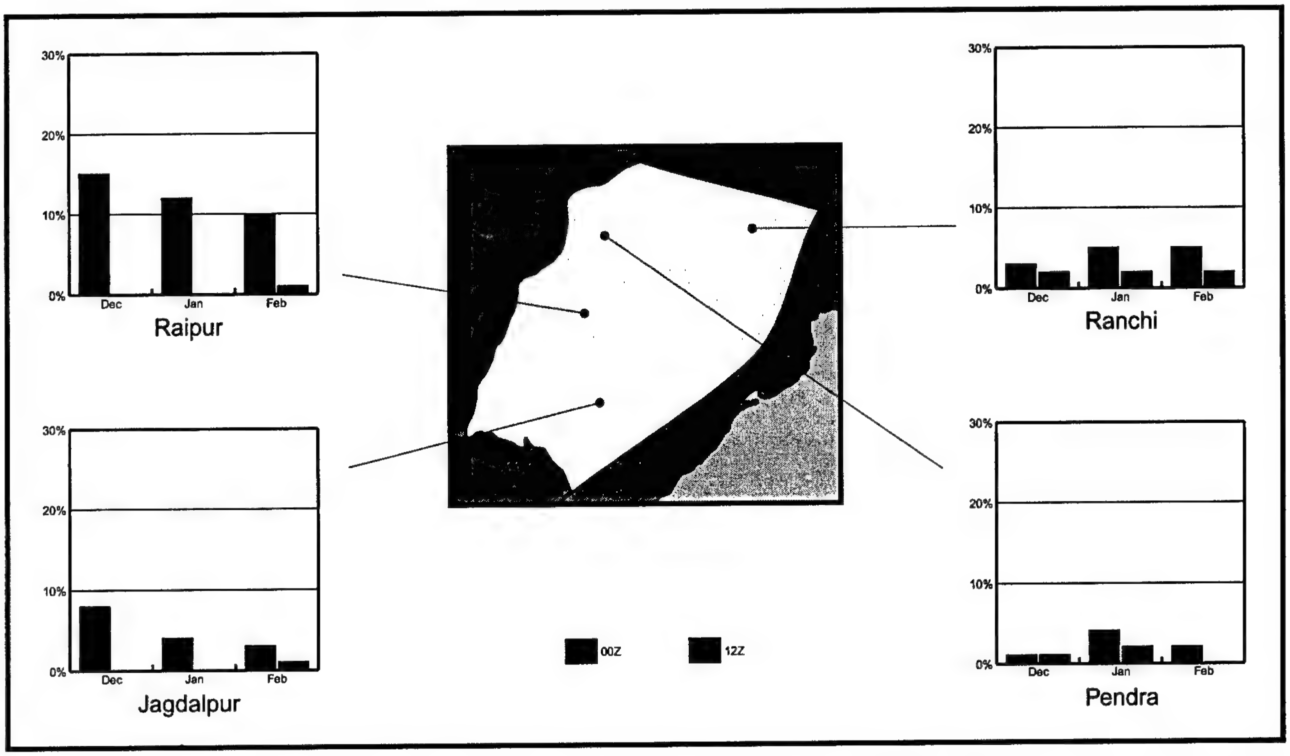


Figure 4-4. Winter Percent Frequency of Visibility below 2 1/2 miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. In the northeast monsoon, surface winds are generally from the northwest to northeast at 5-10 knots, but local winds vary greatly from this according to terrain, as noted in Figure 4-5. Calm winds are most common overnight and in the early morning hours.

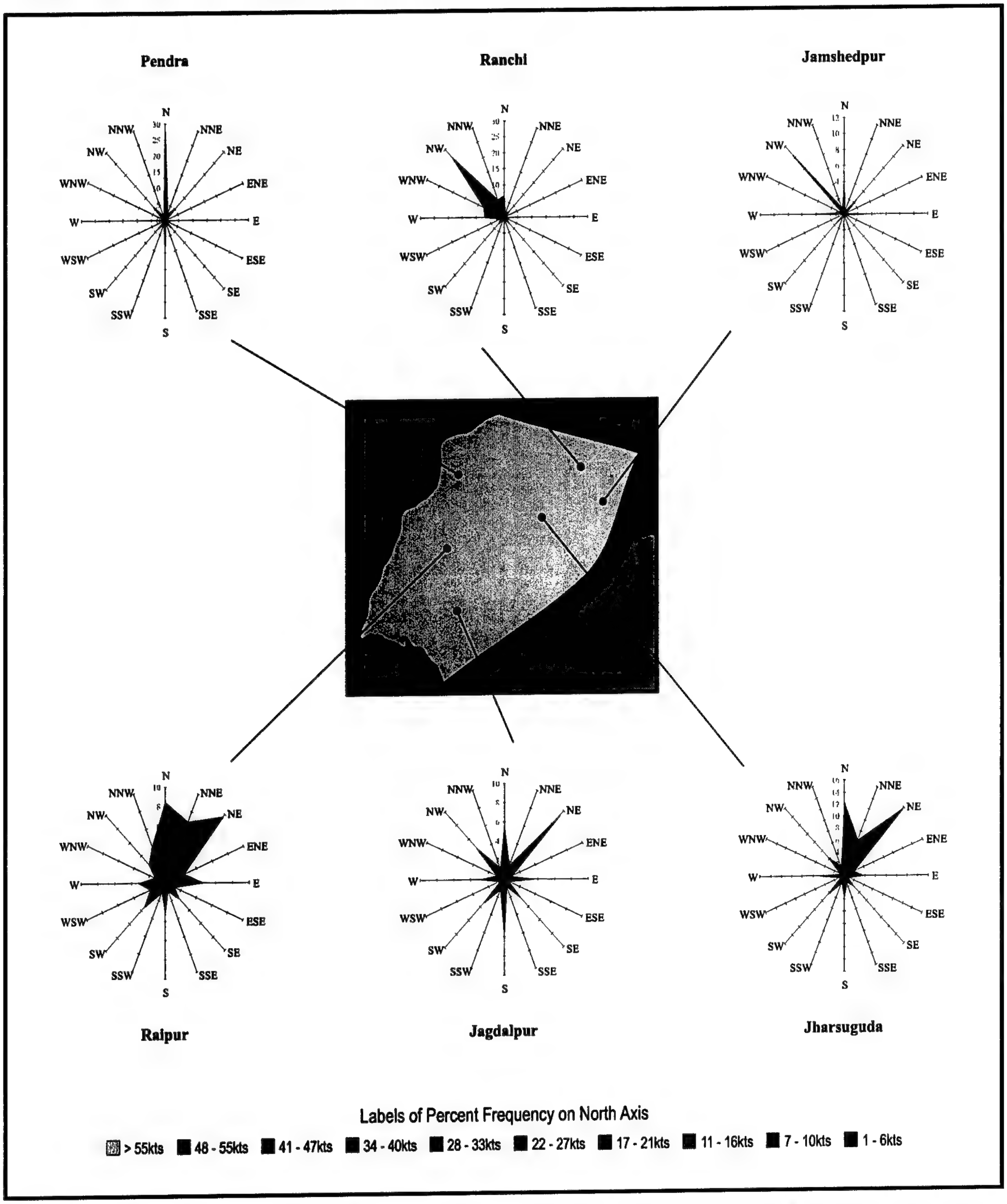


Figure 4-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. December 850-mb winds are northwesterly at 10 knots in the northern half of the region and variable at 10 knots in the southern half. In January and February, they are northeasterly at 5-10 knots. From December through February, the 700-mb winds are weakly easterly at 5-10 knots in the rest of the region. At 500 mb, westerly winds dominate the season. In the north, they are 40 knots. In the southern areas, the are only 10-15 knots. Westerlies rule at 300 mb as well; there they are 70-75 knots in the north and 25-30 knots in the south. The subtropical jet, in the north area, averages 95-105 knots at 200 mb. See Figure 4-6 for

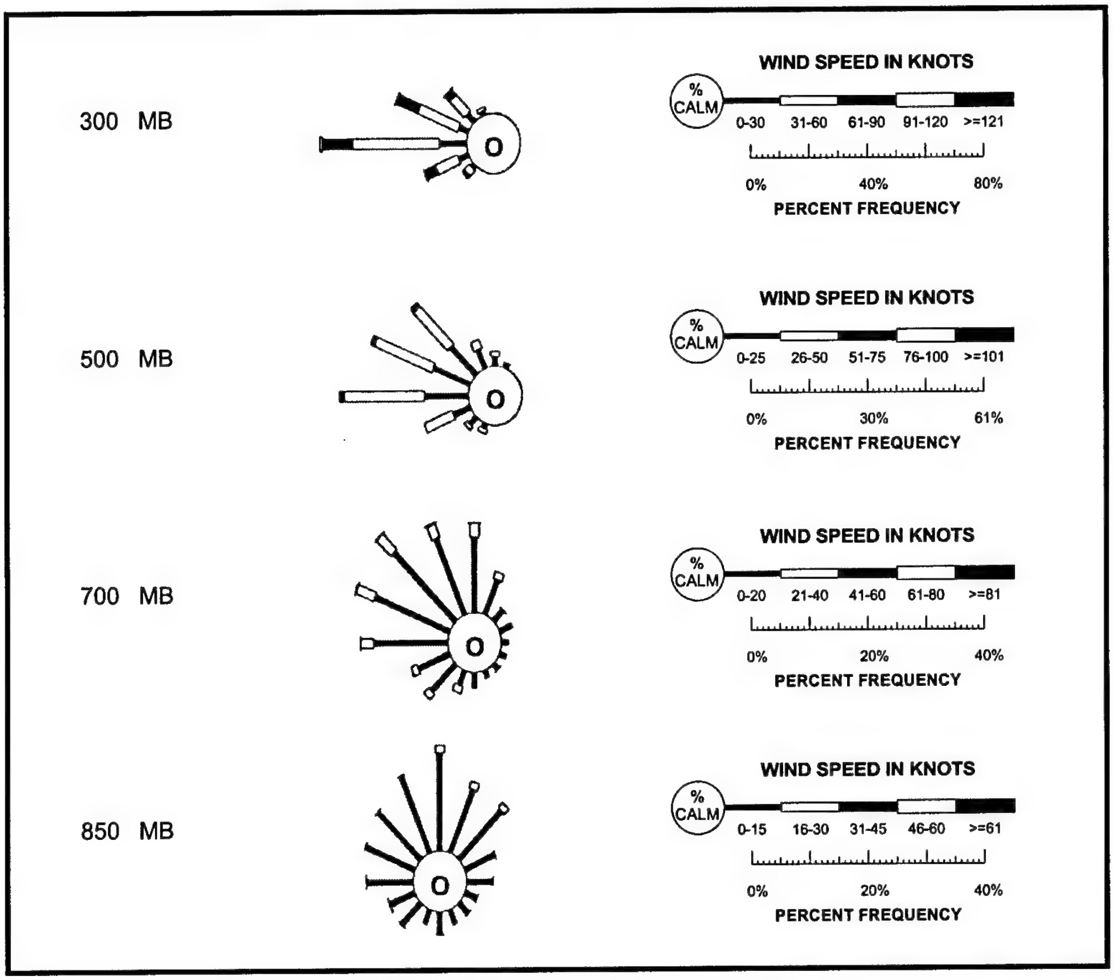


Figure 4-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Jagdalpur.

wind roses for Jagdalpur. Page Before

Precipitation. The region averages less than 0.7 inch (18 mm) of rain in December and January. December is slightly drier than January and February is wetter. The farther inland a location, the less rain it gets. In February, the average is 0.5-1 inch (13-25 mm). The eastern slopes of the Eastern Ghats and on eastern slopes of higher elevations in the northern areas of the region get slightly more, up to 1.5 inch (38 mm). Figure 4-7 shows the January mean precipitation. Rain falls 1-3 days per month all season. Thunderstorms occur least in this season throughout the region. Most places have 0-1 thunderstorm days per month all season. Pendra, in the northwestern corner of the region, and Ranchi, in the northeastern corner, both back up against higher elevations. Moisture and instability from western disturbances (at peak strength in February) fire convection in the mountains of the northern plateau. They have 0-1 thunderstorm day in December, 1-2 days in January, and 3-4 days in February. Figure 4-8 shows the mean winter season precipitation and thunderstorm

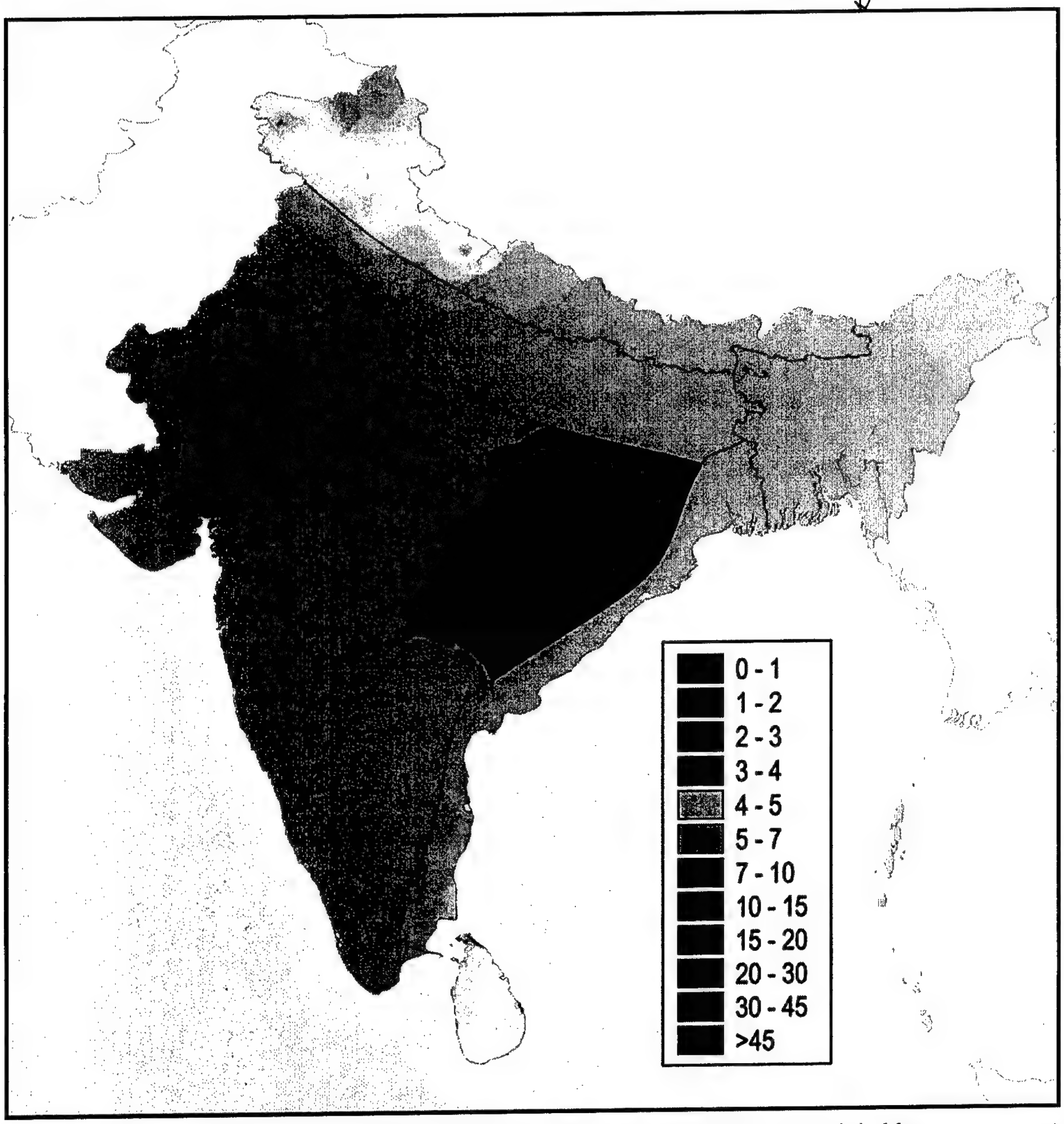


Figure 4-7. January Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

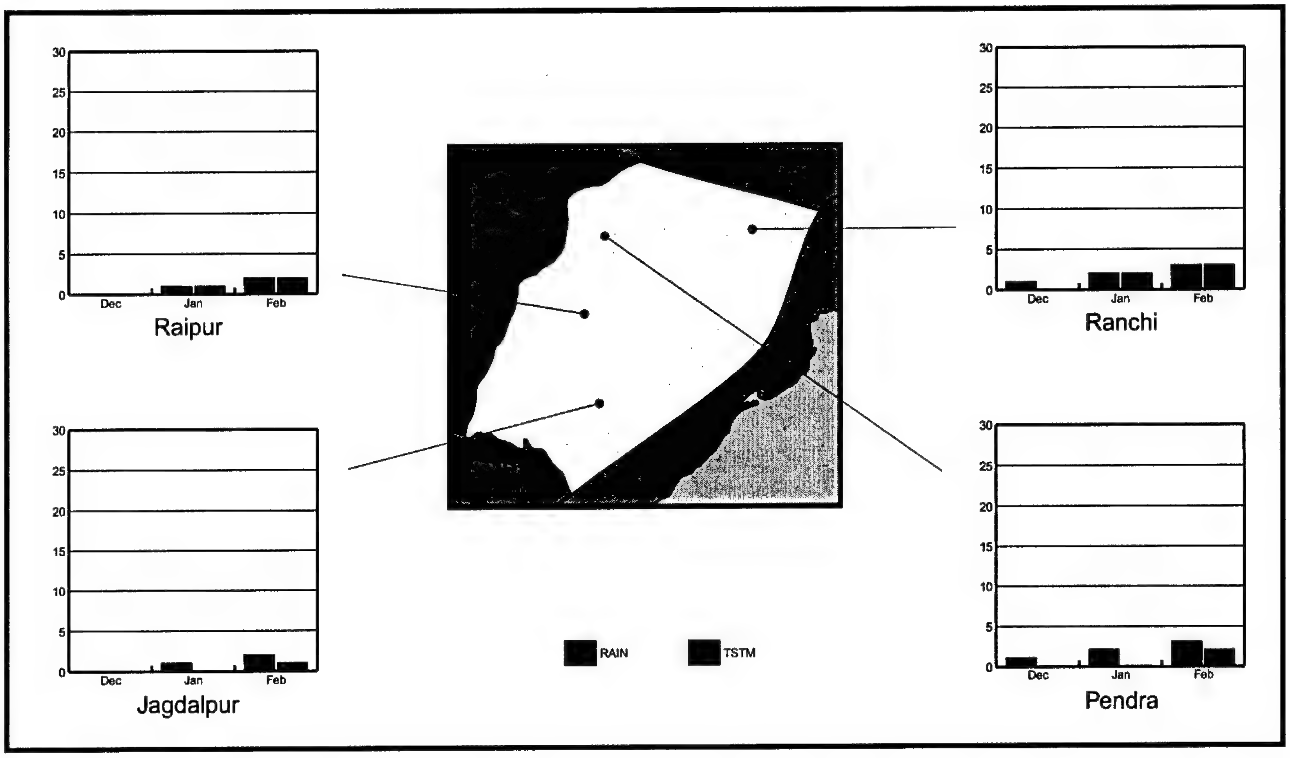


Figure 4-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Winter is generally the coolest season. The temperature does not fall below freezing anywhere. In general, temperatures are higher in the south and the diurnal range is greater inland than close to the coast. December and January temperatures are similar, but February temperatures are 3-6 Fahrenheit (1-3 Celsius) degrees higher almost everywhere. Mean highs in December and January vary from 73° to 77°F (23° to 25°C) in the north to 82° to 88°F (28° to 31°C) in the south and central areas. Mean lows in the same period are 48° to 52°F (9° to 11°C) in the northern interior to 54° to 57°F (12° to 14°C) in the central areas, to 56° to 65°F (13° to 18°C) in the south close to the coast. Figures 4-9 and 4-10 show the January mean maximum and minimum temperatures, respectively.

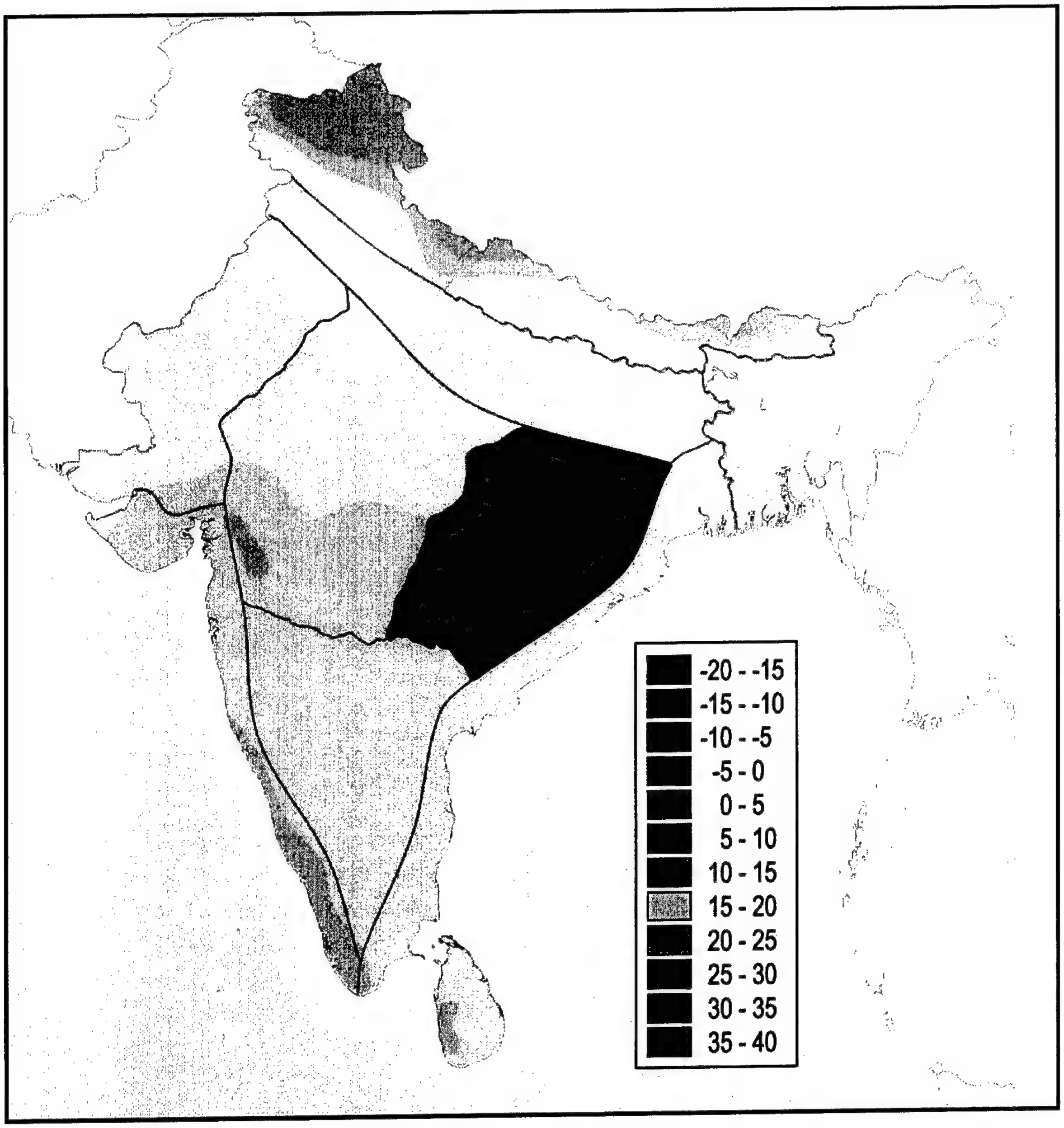


Figure 4-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during other months may be lower or higher, especially at the beginning and ending of the season.

Extreme highs occur in El Niño years with widespread drought conditions. In December and January, the extreme highs are 88° to 93°F (31° to 34°C). In February, they are 98° to 103°F (37° to 39°C). Extreme lows are associated with cold air surges behind western disturbances that bring cold air over the western mountains. The extreme lows are coldest in the northern third of the region, 36° to 42°F (2° to 6°C) and warmest in the southern third, 48° to 52°F (9° to 11°C).

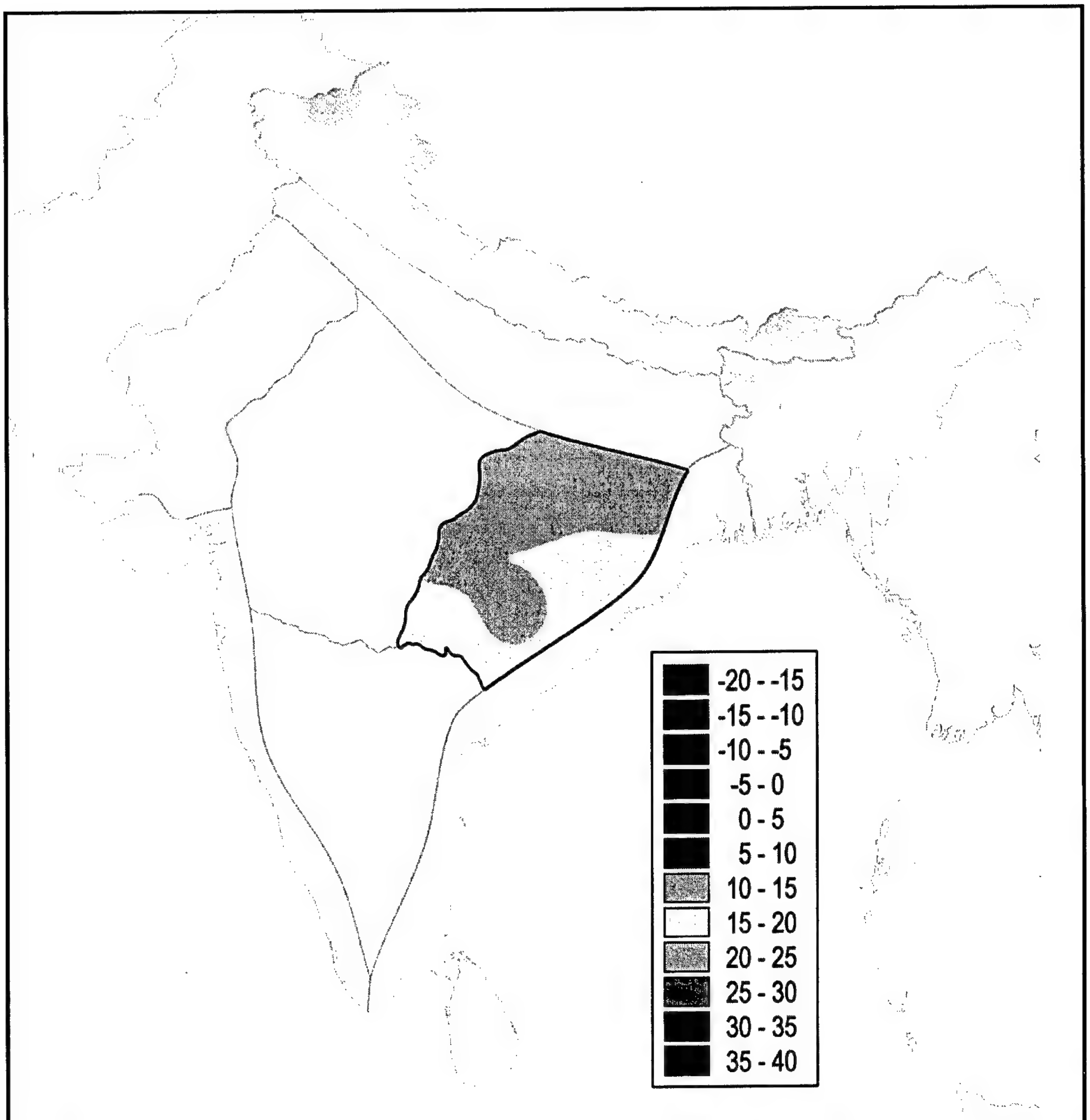


Figure 4-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other winter months may be lower or higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This is when the hot, dry weather reaches its peak. The subtropical jet that moved migratory lows through in the winter now lies mostly north of the Himalayan massif. Also, the thermal high over Asia is seriously weakened in March, and the induced leeside trough at the southern foot of the mountains is no longer a favored track for passing lows (western disturbances). This moves the storm track from the southern flanks of the Himalayas to north of the range, and few lows move across northern India as a result. The thermal low over Australia disappears, and the equatorial trough (ET) heads north with the sun.

April-May is when the ET crosses over the southern part of the peninsula at the leading edge of the southwest monsoon air mass. There is considerable variance in onset of the southwest monsoon across the region. The

days

rains begin at almost the same time on the southern tip of the peninsula and in the northeast corner of the Bengal basin to Assam (East India) in mid-May. It takes another month and a half for all of India to be fully under the southwest monsoon regime. The northward travel ofthe ET is not a smooth, steady one. It oscillates north and south, moves many miles in surges then retreats, and stagnates in one place for days at a time. In this transition season, "onset vortices" travel along the ET at the leading (northern) edge of the southwest monsoon air mass. These vortices produce rain, rainshowers, and thunderstorms and signal the "monsoon burst" of the changing season. The hottest weather of the year ends in this transition. Although not common, tropical cyclones do develop in the Bay of Bengal in the hot season. Their mean track brings them ashore on the northeastern coast. They are more likely to occur in May, with the ET as it shifts north, than in April.

Sky Cover. At most places, cloudiness increases in May as the southwest monsoon approaches. The proportion of low cloudiness also increases as the season progresses. Those areas close to the east coast have the most cloud cover, 35-45 percent at mid-season and 50-60 percent in May. Farther inland, it is 25-35 percent at mid-season and 40-50 percent in May. The diurnal cloud maximum occurs in late afternoon, and the minimum occurs in the hours before dawn.

Morning ceilings below 5,000 feet occur 5 percent of the time or less all season in most of the region. In the north and in the Eastern Ghats, they occur 10-15 percent of the time in March and April and 25-30 percent of the time in May. At midday, even those areas have ceilings below 5,000 feet less than 10 percent of the time. Places at lower elevations rarely have them. Late in the afternoon, cloudiness peaks and ceilings below 5,000 feet occur 10-15 percent of the time everywhere but in the highlands of the north and the Eastern Ghats. There, they occur 15-20 percent of the time in March and April and 35-40 percent of the time in May. After sunset, cloud cover below 5,000 feet lessens to occur under 10 percent of the time in most places. In the north and the Eastern Ghats, they occur 10-15 percent of the time in March and April and 15-25 percent of the time in May. Ceilings below 1,000 feet rarely occur anywhere in the region all season. They are most likely under heavy rainshowers in late May.

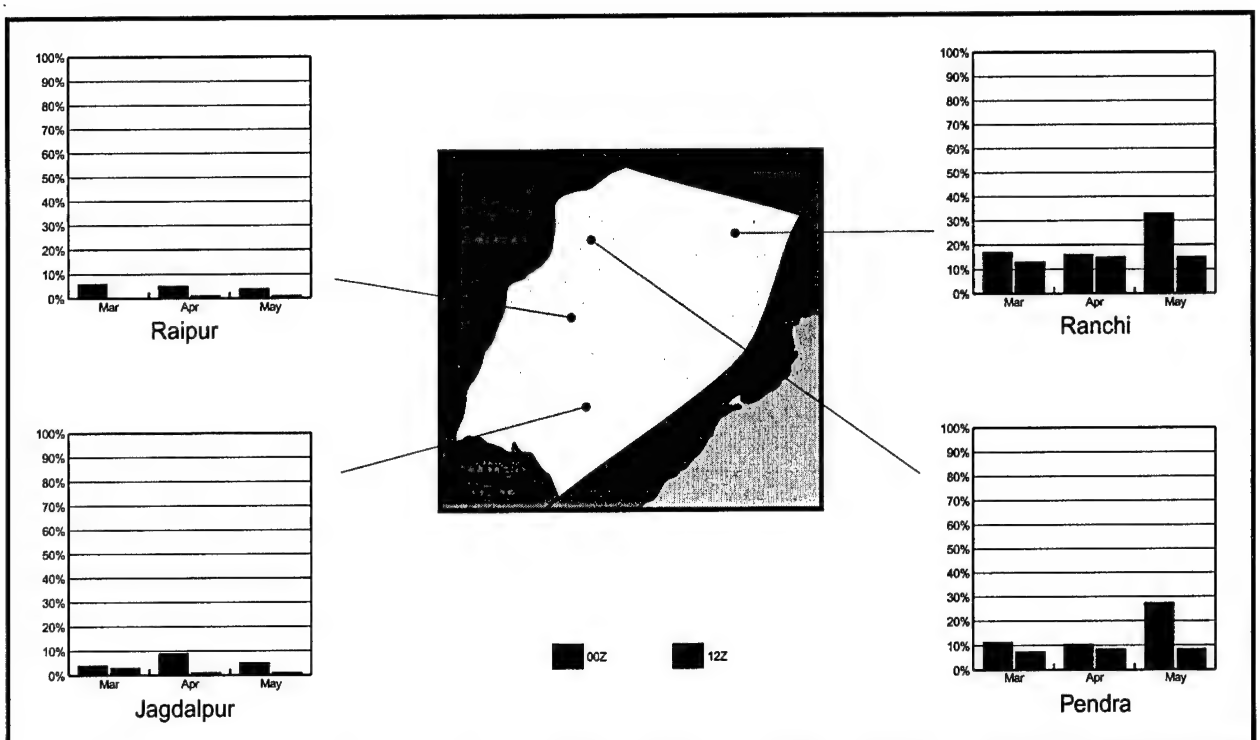


Figure 4-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is most restricted by dust. Dust conditions are worst in heavily trafficked areas where the wind picks up the fine soil particles. Smog in urban industrial areas keeps visibility below 6 miles (9,000 meters) but rarely restricts it to below that for long. Morning fog around rivers dissipates quickly.

Visibility below 2 1/2 mile (4,000 meters) occurs most in March in the lowlands near rivers in early morning fog. March morning visibility below 4,000 meters occurs 10-15 percent of the time in the lowlands and 4-8 percent of the time everywhere else. By April, lowland areas have morning visibility below 4,000 meters 5-10 percent of the time and other areas rarely get it at all. By May, as humidity and rains increase, the rate drops again to under 5 percent of the time in lowland areas. The rest of the day, visibility below 4,000 meters rarely occurs anywhere in the region except in convective precipitation, most likely in late May. See Figure 4-12 for seasonal percent frequency of visibility below 4,000 meters within the region. Visibility below 1 1/4 miles (2,000 meters) occurs only with convective precipitation and is short-term.

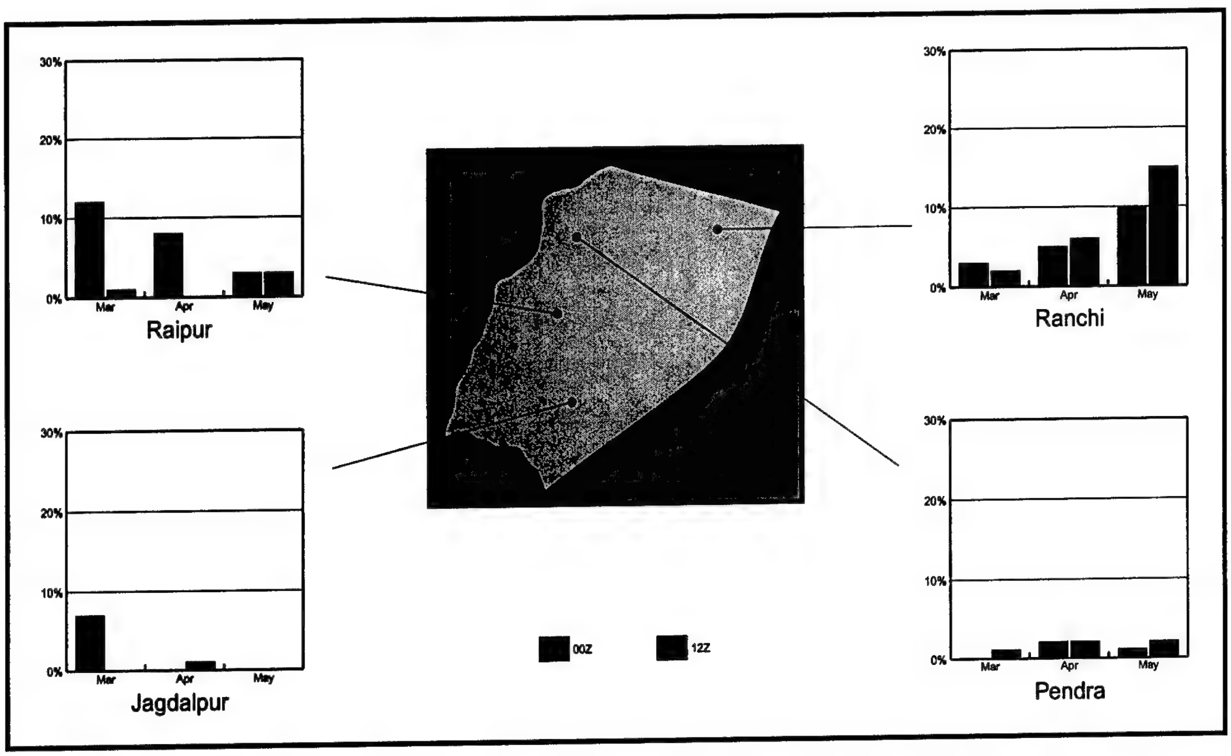


Figure 4-12. Hot Season Percent Frequency of Visibility below 2 1/2 miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Winds gradually change from prevailing northeast winds at 5-10 knots to southwest winds at 8-12 knots. Directions and speeds will vary greatly from the prevailing winds under the influence of local terrain features. Overnight and early morning calms are less and less common as the season progresses. In the vicinity of lakes and rivers, lake breezes begin to occur in the afternoons. They die off at sunset. Figure 4-13 depicts surface winds in April for various locations within the region.

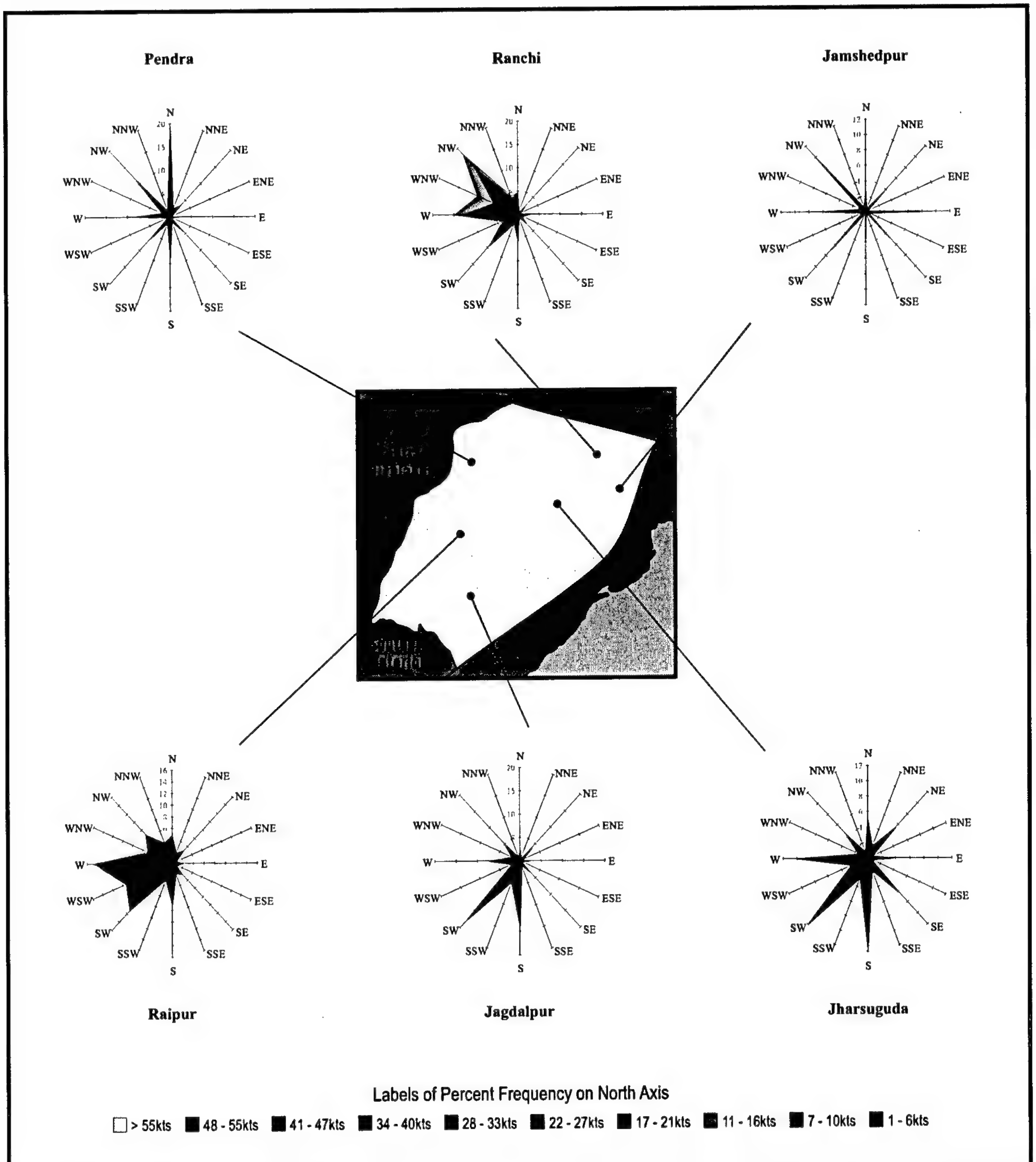


Figure 4-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. In March, 850-mb winds are northeasterly at 5-10 knots. In April and May, variable winds begin to blow mainly from the west at 5 knots by May. At 700 mb, winds vary from northeast to southeast at 5-10 knots all season. At 500 mb, west to northwest winds at 35-40 knots prevail in the north while westerly winds blow at 5-10 knots in the rest of the region. At 300 mb, west winds at 15-25 knots prevail. The upper-level winds for Jagdalpur are shown in Figure 4-14.

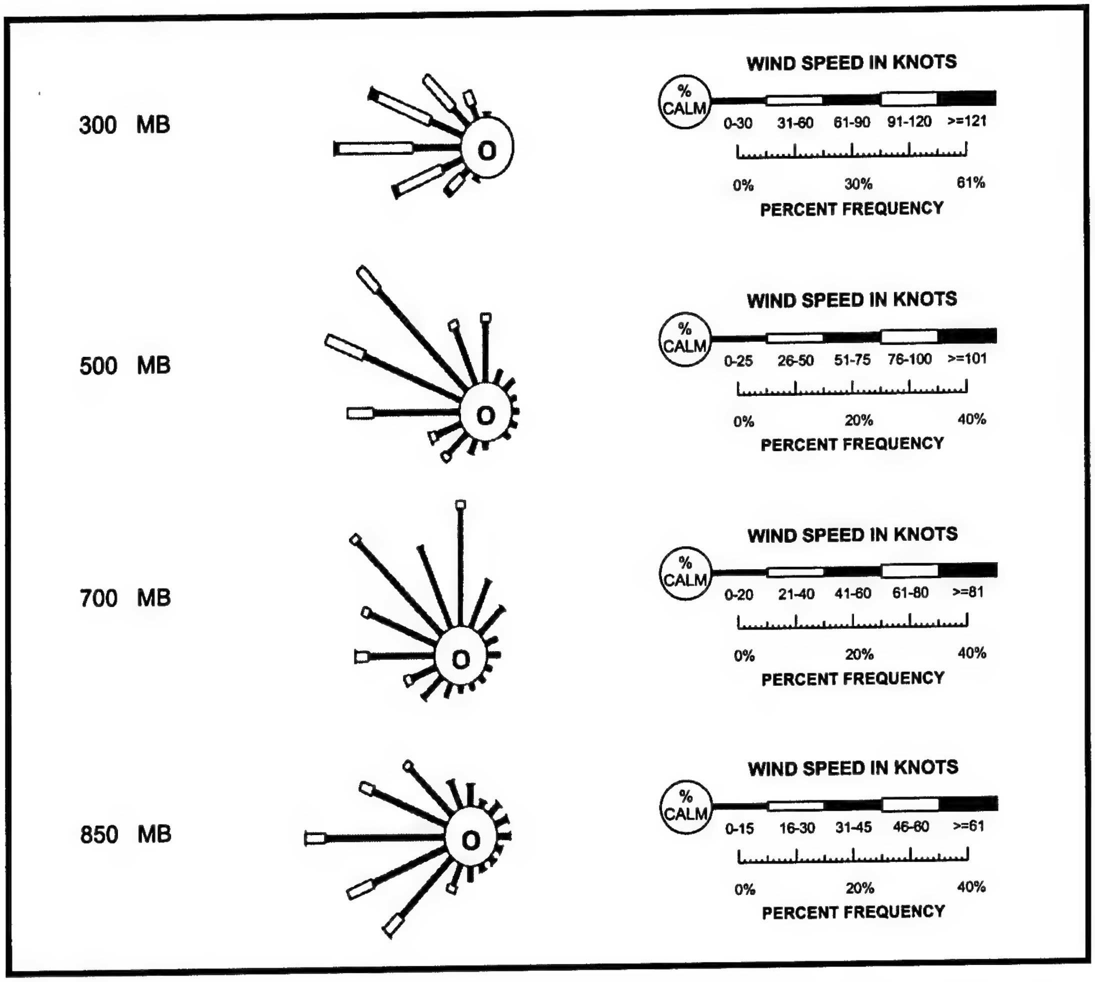


Figure 4-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Jagdalpur.

Precipitation. Rain is very light in March and April; many areas in the plateau interior get a trace of rain or none. Close to the east coast, the average is 0.5-1 inch (13-25 mm). In May, the amount rises to 1.5-2.5 inches (38-63 mm) everywhere as the monsoon trough (ET) shifts northward and pre-monsoonal rains begin to reach the region. Measurable rain falls 1-3 days per month in March and April and 2-5 days in May. The early-year thunderstorm maximum begins in May, but March and April tend to have 3-5 thunderstorm days per month. Many of these thunderstorms are dry or have only virga. Thunderstorms carry more rain in May and occur 6-10 days with more at the end of the month then at the beginning. Figures 4-15 and 4-16 show the mean precipitation amounts in April and the mean seasonal rain and thunderstorm days, respectively.

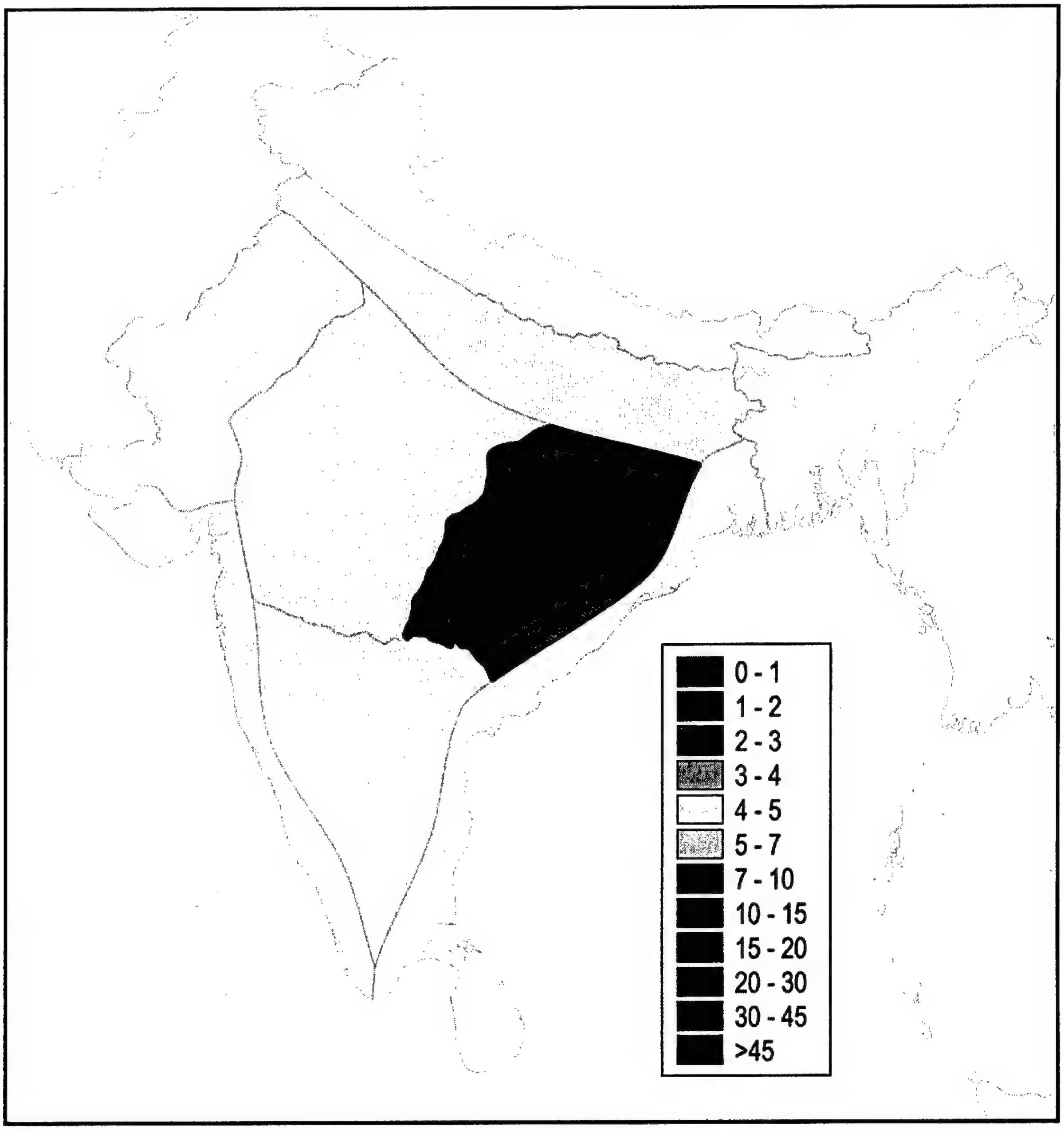


Figure 4-15. April Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

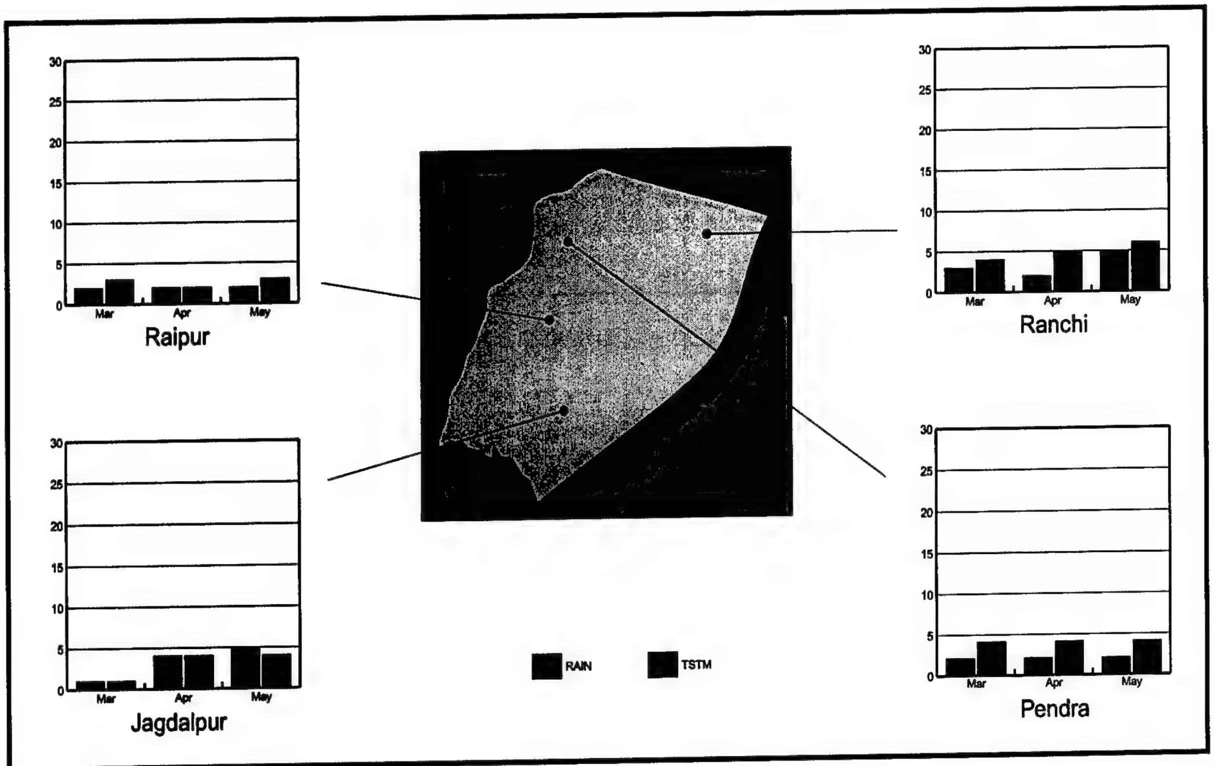


Figure 4-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The highest afternoon temperatures on the peninsula occur at interior locations of this region. March and April mean highs are 85°-90°F (29° to 32°C) in the north half of the region and 95° to 100°F (35° to 38°C) in the south half. May is usually the hottest month; mean highs at all interior stations exceed 100°F (38°C). The southwestern corner of the region has the hottest temperatures. Raipur has a mean high of 107° (42°C) in May; areas farther southwest have means of 110°F (43°C). Moisture modifies the temperature close to the coast to May mean highs of 90° to 100°F (32° to 38°C). Elevation cools the air moist adiabatically. Mean lows

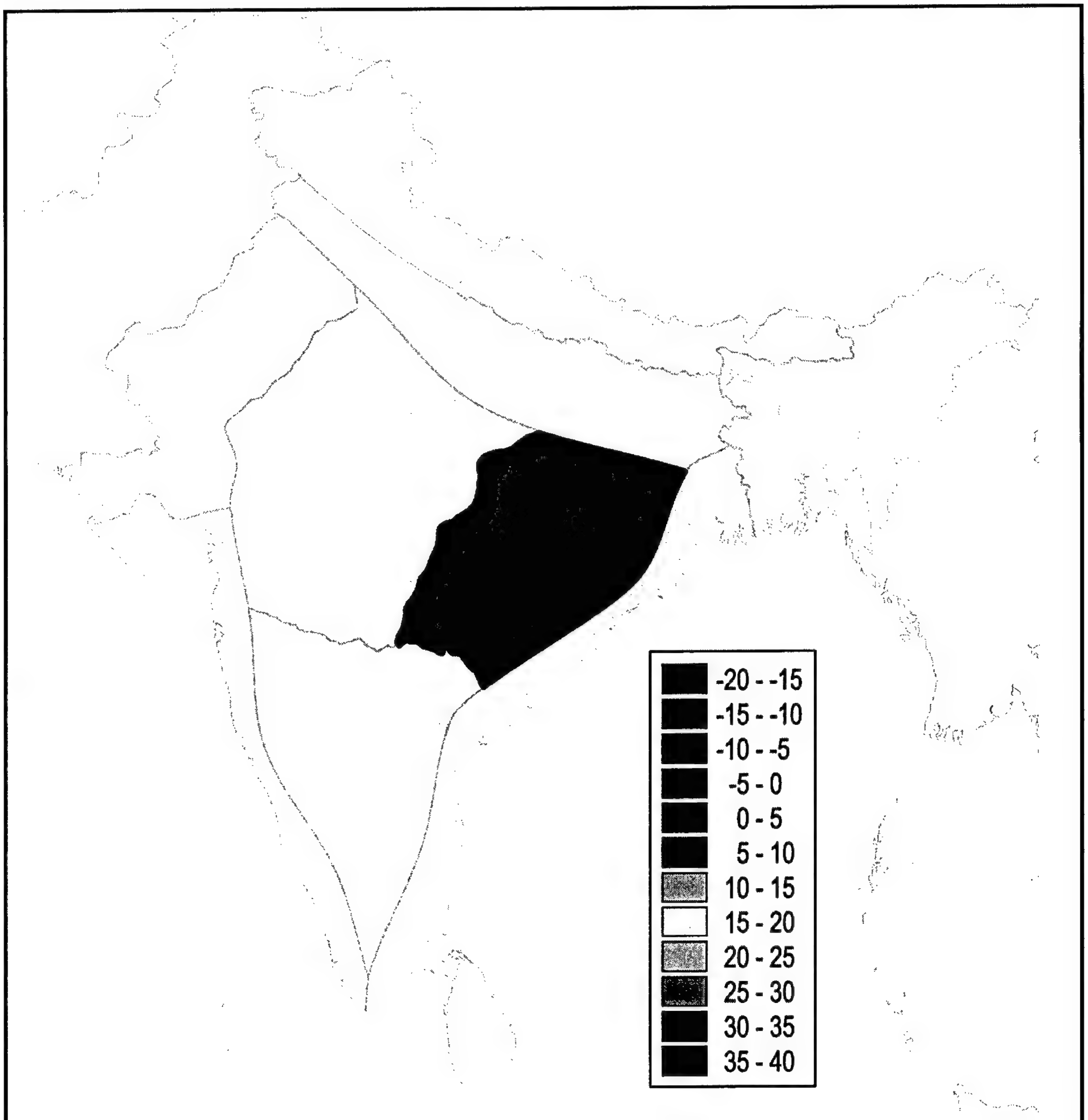


Figure 4-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during other months may be lower or higher, especially at the beginning and ending of the season.

in March are 62° to 68°F (17° to 20°C) in the northern half of the region and 68° to 73°F(20° to 23°C) in the southern half. In April, mean lows rise to 70° to 76°F (21° to 24°C) in the whole region. Mean lows rise again in May to 75° to 82°F (24° to 28°C). At the end of May, the weather cools with the onset of monsoon rains.

Extreme highs exceed 120°F (49°C) in the interior lowlands areas and 110°F (43°C) in the highlands. These extreme highs are most probable in El Niño years, when drought is widespread in the region. Extreme lows are coolest in March, 45° to 55°F (7° to 13°C), and warmest in May, 59° to 67°F (15° to 19°C). The coolest extreme lows are in the northern half of the region.

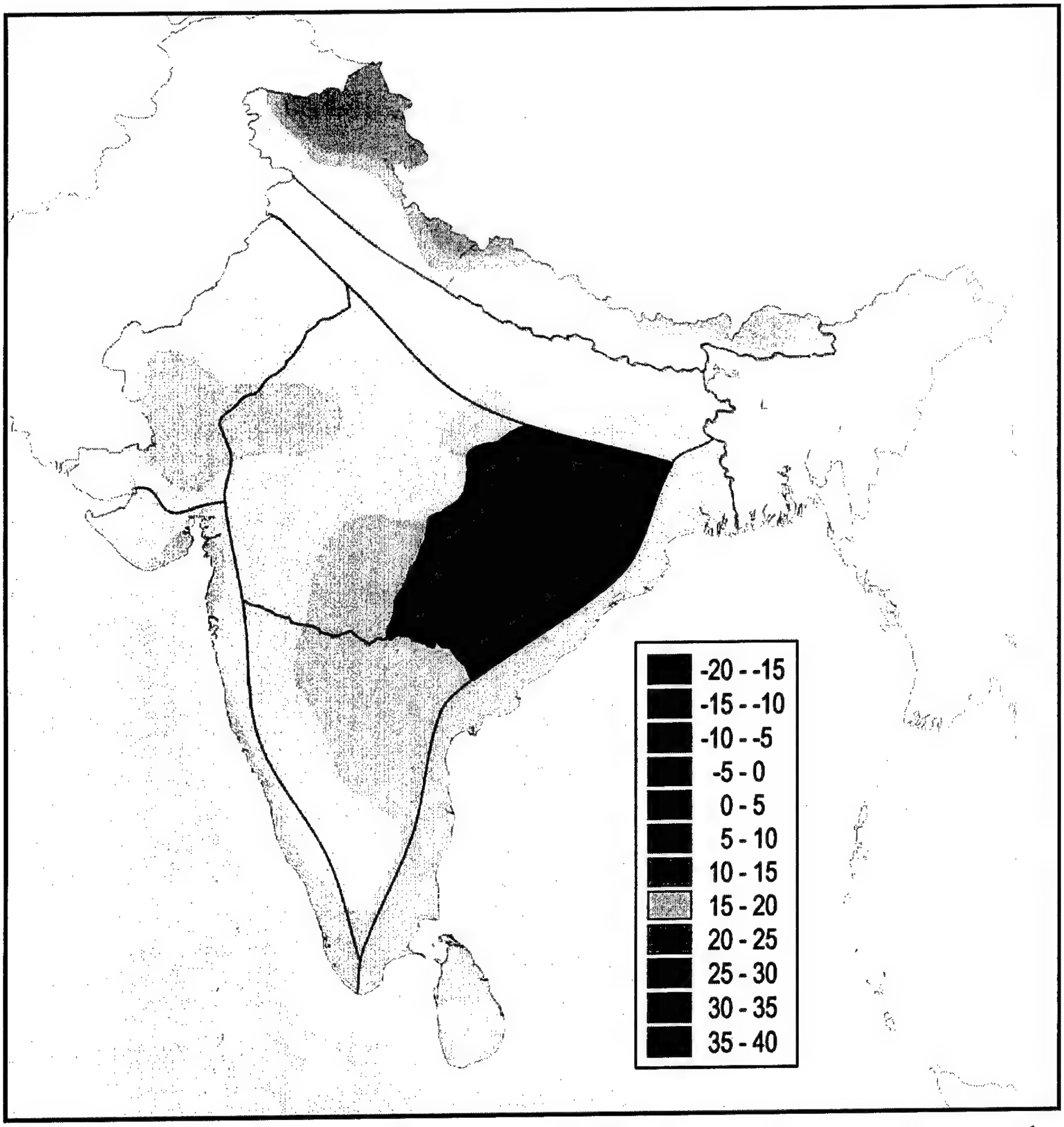


Figure 4-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during other months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. The equatorial trough (ET) moves into the area with overall southwest flow. Although generally thought to begin in June, the monsoon actually begins as early as mid May on the southern tip of the peninsula and in the northern areas. The rest of the region gets the southwest monsoon in stages from south to north. By the end of June, the whole region is under southwest monsoon flow. By July and August, the ET is as far north as it gets and easterly flow aloft is almost to the foot of the Himalayas. The India-Myanmar trough sets up in this season. This southwest-northeast oriented trough develops over the Bay of Bengal and is a prime breeding ground for monsoon depressions. Easterly waves and other tropical disturbances are enhanced when they make their way into this convergence zone and sometimes develop into full-blown tropical cyclones.

Mean tropical cyclone tracks are generally in the northern Bay of Bengal. In June and July, most storms tend to make landfall in the northeastern corner of the bay. In August through October, the tracks shift south slightly.

The equatorial westerlies are a hallmark of the southwest monsoon season. Created by deflected outflow of the South Indian Ocean high, these low-level winds spread out over the north Indian Ocean. At the same time these winds begin to flow, the Somali jet develops. This low-level jet transports Southern Hemisphere air across the equator. This warm, moisture-laden air is what makes the southwest monsoon season rainy. The tropical easterly jet (TEJ), which is a southwest monsoon feature, provides an upper-level exhaust for Bay of Bengal convection. The bay is a prime zone for the development of tropical cyclones, monsoon depressions, and other cyclonic storms. Fortunately, storms in the Bay of Bengal are so confined in the enclosed bay, they do not become as powerful as open ocean storms can. They can still carry high winds, heavy surf, and vast amounts of precipitation.

The deep, wide band of upper-air easterlies overlay the equatorial westerlies. During this season, the easterlies are strongest and spread farthest north, almost to the foot of the Himalayas. Easterly waves ride this powerful current of air and trigger off the development of monsoon depressions and tropical cyclones. By the end of the season, the band of easterlies retreats southward toward the equator.

Thermal lows set up over the central Indian subcontinent and over the Tibetan Plateau. The Indian low becomes part of the greater Asiatic low and trough that extends from northwestern India to the Sahara. This is a source region for migratory lows that move across the subcontinent and into the Bay of Bengal. Over-lying the Tibetan low is the Tibetan anticyclone, which develops in the zone between the strong, deep westerlies of the Northern Hemispheric midlatitudes and the strong, deep easterlies of the low latitudes. The stronger the thermal low, the stronger the anticyclone. The southern edge of this anticyclone is a prime area for the development of monsoon depressions and other cyclonic storms, especially in the Bay of Bengal.

Sky Cover. Skies are cloudy this season, but ceilings below 1,000 feet are still not common; they occur less than 5 percent of the time in most places. At the height of the monsoon, 20-30 afternoons per month are cloudy everywhere and clear periods that last more than a few hours are rare. There is little diurnal variation in cloud cover and stratiform clouds are the dominant type. Cloud cover is at a maximum in July and August and averages 85-95 percent during the day.

Ceilings below 5,000 feet occur more in the east half of the region than in the west and more over higher elevations in the north and the Eastern Ghats than in the lowlands (see Figure 4-19). At higher elevations, June ceilings below 5,000 feet occur 50-60 percent of the time most of the day and 75-85 percent of the time in the late afternoons. At lower elevations, they occur 15-25 percent of the time most of the day in June and 30-45 percent of the time in the afternoons. July and August have the highest occurrence rates of the year. Ceilings below 5,000 feet occur 55-70 percent of the time most of the day, but at midday, the rate rises to 75-85 percent of the time then eases off again by late in the afternoon. At higher elevation, especially on windward slopes, the occurrence rate remains high throughout the day, 75-85 percent of the time most of the day and up to 95 percent of the time in the afternoons. By September, rates decline as the southwest monsoon moves south. Ceilings below 5,000 feet occur 45-60 percent of the time in the lowlands and 55-65 percent of the time in the highlands, with the maximum rate in the afternoons.

Ceilings below 1,000 feet occur far less often than those at higher levels. In June and September, ceilings below 1,000 feet are uncommon; even at higher elevations they occur 10 percent of the time or less. For most places, they occur less than 5 percent of the time. In July and August, they occur more, as often as 15 percent of the time on windward slopes of higher elevations. In the lowlands, they still occur 5 percent of the time or less. Windward slopes are likely to be cloud-cloaked for much of the day, especially in July and August.

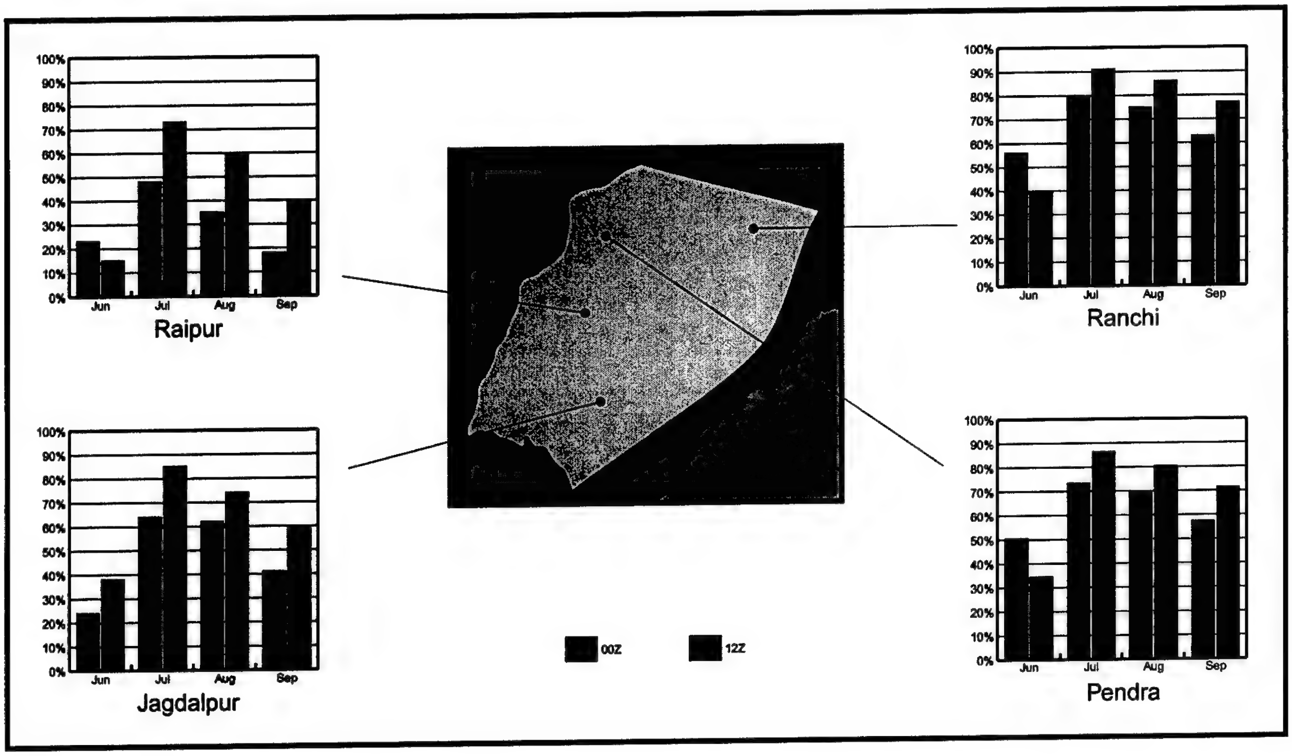


Figure 4-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility improves with the rain as it cleans the air of dust particles. Rain and fog restrict visibility. Fog is most prevalent in the early mornings, especially around rivers and on windward slopes of higher elevations. Rain restricts visibility most in heavy rainshowers and thunderstorms, but this is a short-term reduction. Steady rain restrictions are considerably less, and visibility is usually 6 miles (9,000 meters) or better outside of heavy precipitation. Urban industrial areas improve, but smog is a continuing problem.

Visibility below 2 1/2 miles (4,000 meters) occurs 10-15 percent of the time in the mornings in places at higher elevations, the most in windward sites. In the lowlands, it occurs 5 percent of the time or less. In the southwestern corner of the region, it occurs only rarely around the river. By afternoon, visibility below 4,000 meters occurs 5-10 percent of the time at higher elevations and well under 5 percent of the time in the lowlands. Visibility below 1 1/4 miles (2,000 meters) rarely occurs anywhere in the region. Short-term restrictions below 2,000 meters are likely in convective precipitation.

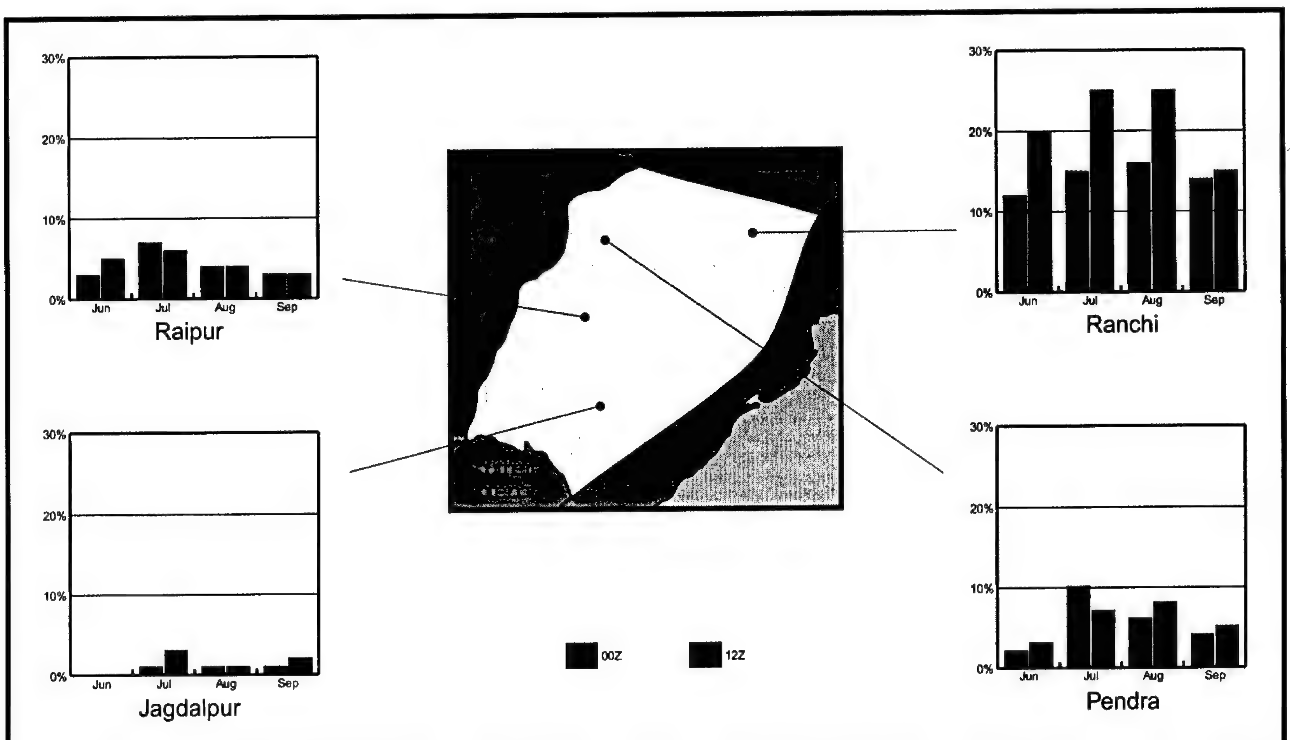


Figure 4-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Prevailing winds are generally from the south or southwest at 8-12 knots, however, local winds will vary greatly under the influence of terrain. Calm conditions are most likely at night and in the lee of mountains, but do not occur nearly as often as they do in the northeast monsoon. Lake breezes begin in the afternoon and die off after sunset. Weaker land breezes toward the lakes start after midnight and fade away near sunrise. Figure 4-21 shows the July mean surface winds around the region.

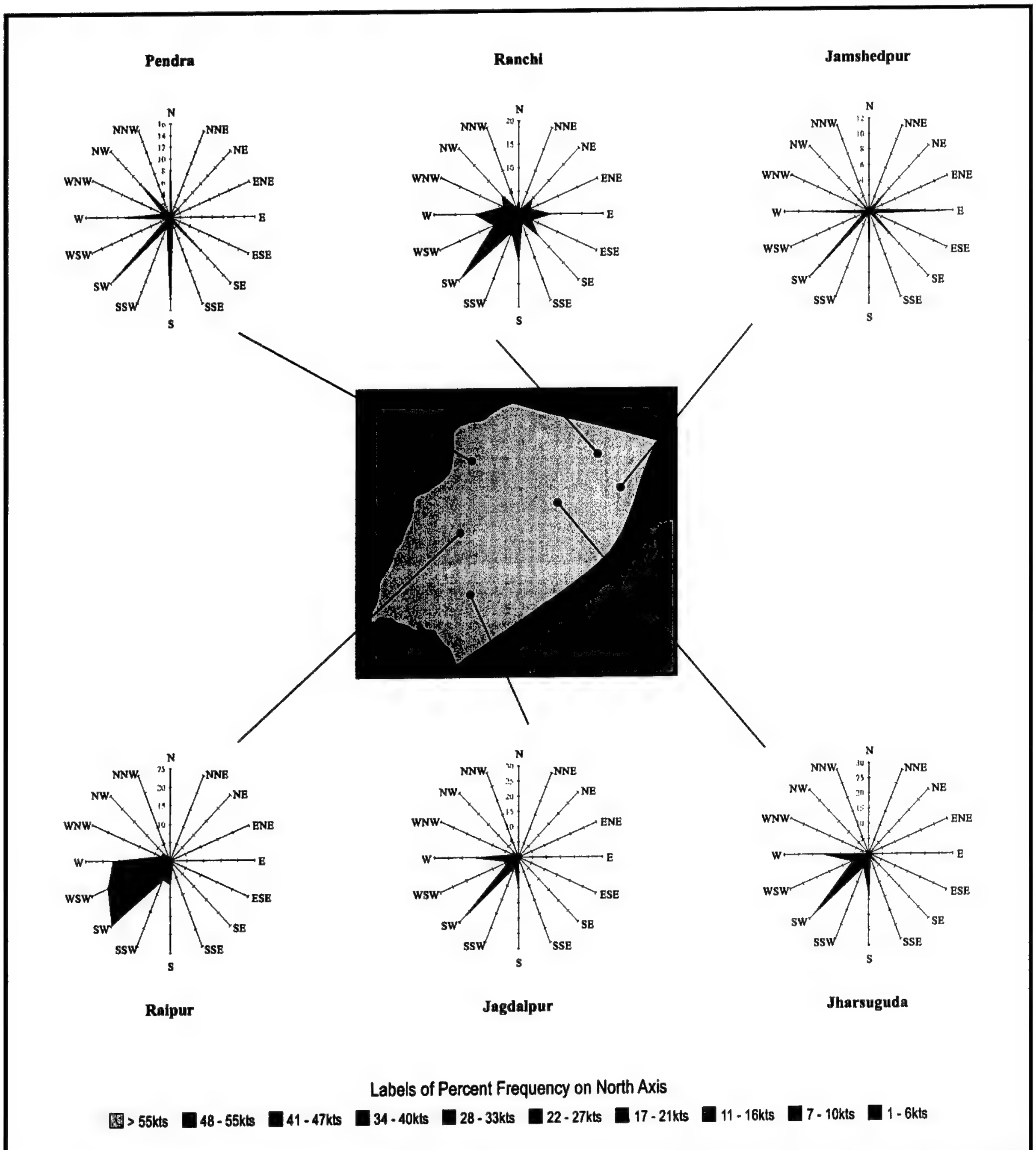


Figure 4-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Winds at 850 mb range from southeast to southwest at 5-10 knots. The 700-mb winds are from the west at 15-20 knots for the whole season. At 500 mb, the region has variable winds that generally come out of the west at 10 knots all season. The 300-mb winds remain from out of the east at 10-15 knots all season. August wind speeds rise to 20 knots from the same direction. Figure 4-22 shows the upper-level winds at Jagdalpur.

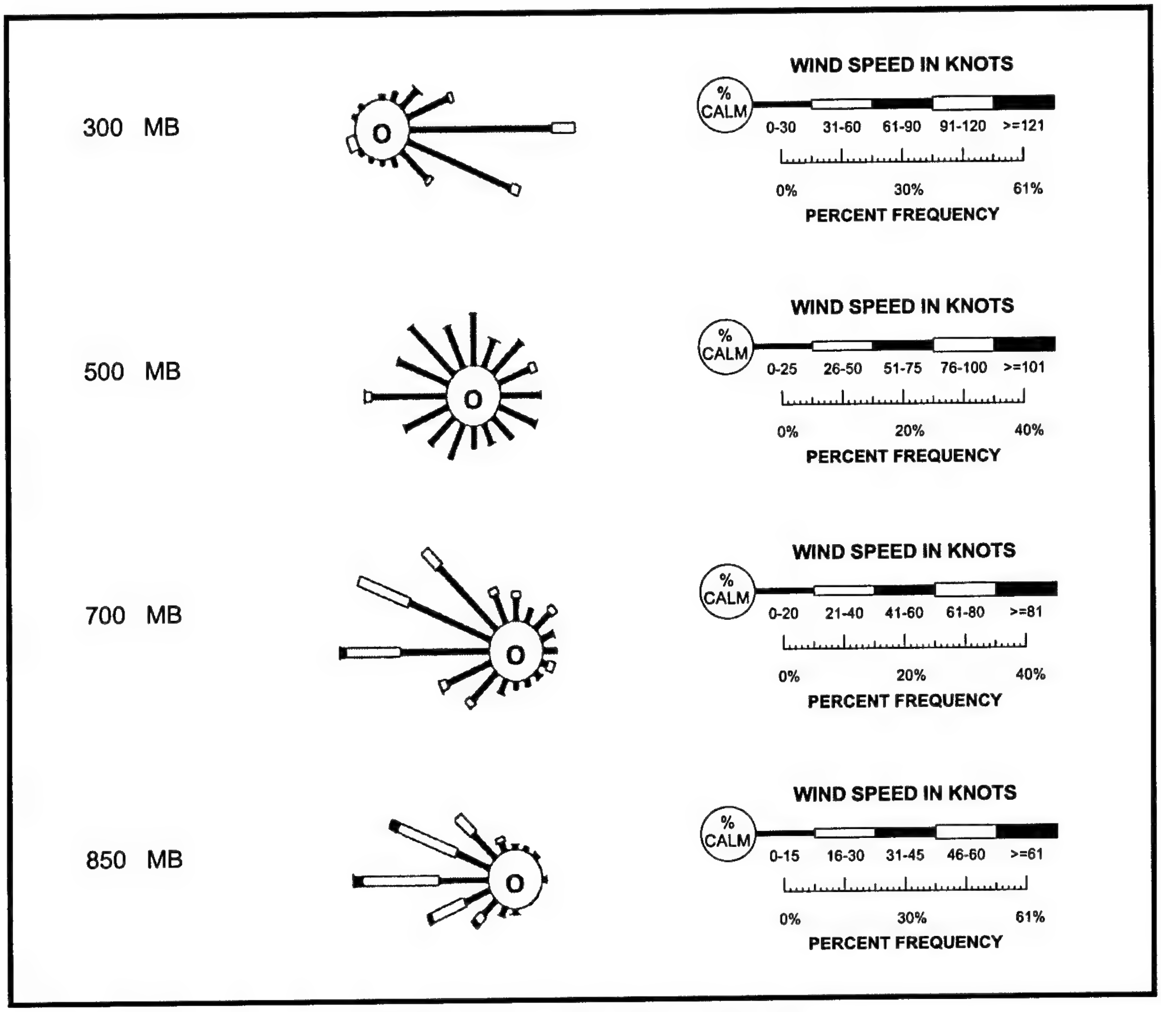


Figure 4-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Jagdalpur.

Precipitation. Throughout the season, the region is influenced by the ET and experiences heavy rains. The higher elevations (Eastern Ghats and the northern plateau) get the most rain. The western areas of the region are under the rain shadow of the western Ghats and get less rain than the eastern-most areas, but still get significant amounts. Most places see a sudden large increase in precipitation in June to 5-9 inches (127-228 mm). July and August are the rainiest months of the year and average 11-18 inches (279-457 mm) of rain per month. September precipitation amounts drop as the ET moves south. The farther from the east coast, the sharper the decrease in rain. Close to the east coast, the average in September is 8-12 inches (203-305 mm). Inland, the average is 3-7 inches (76-178 mm). Figure 4-23 shows the mean precipitation in July.

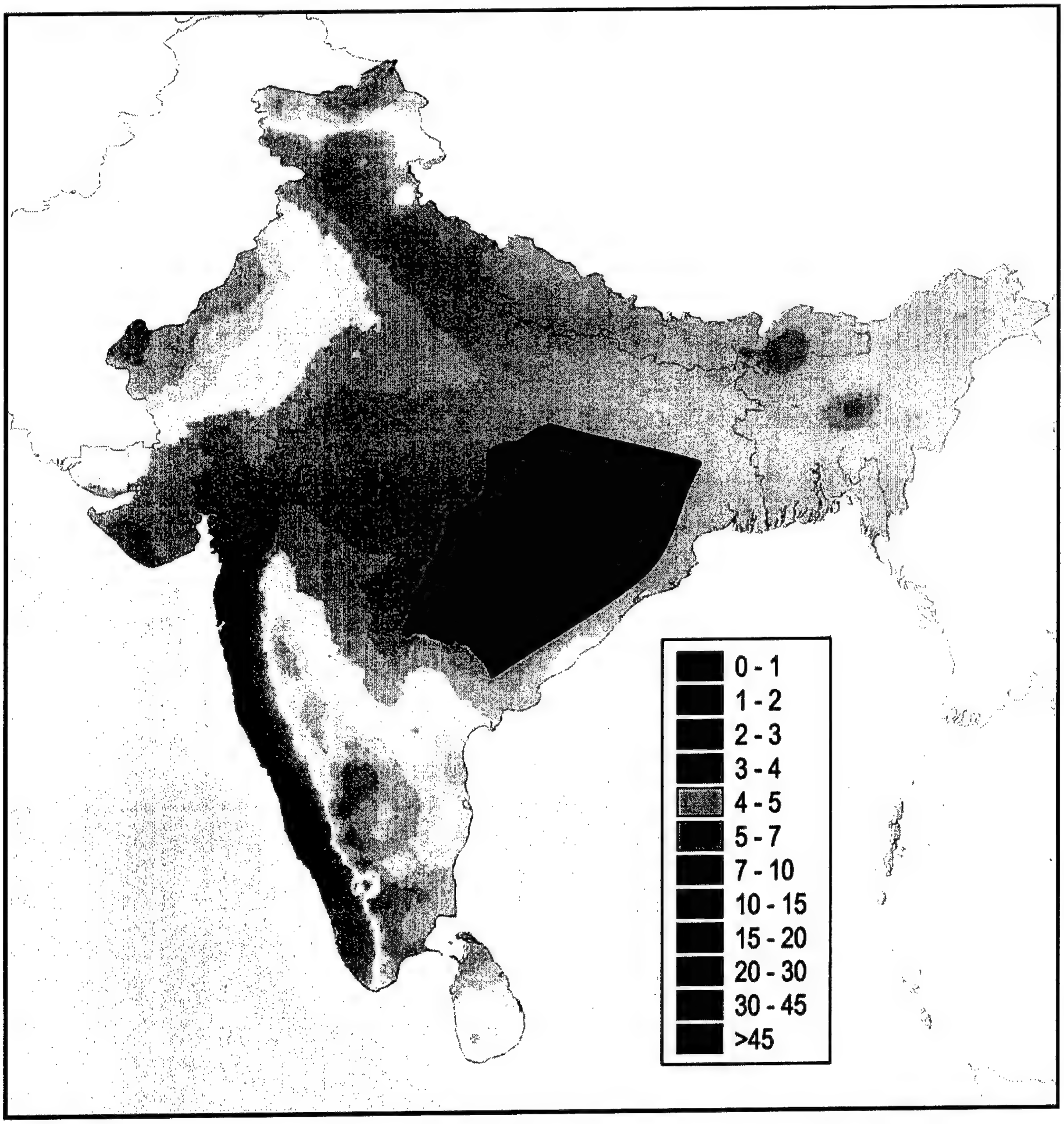


Figure 4-23. July Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

As seen in Figure 4-24, rain falls 7-12 days in June, 16-20 days in July and August, and 10-14 days in September. Thunderstorms occur most in late May through June in association with the advance of the southwest monsoon. In June, they occur 6-9 days in most places, 12-15 days in the southwestern lowlands. In July and August, they occur on 5-9 days per month. In September, they rise again, especially towards the end of the month, to 6-9 days. An exception is Jagdalpur--it has few thunderstorms, only 1-2 per month all season. Jagdalpur is on the leeside of a ridge and is shielded from convection.

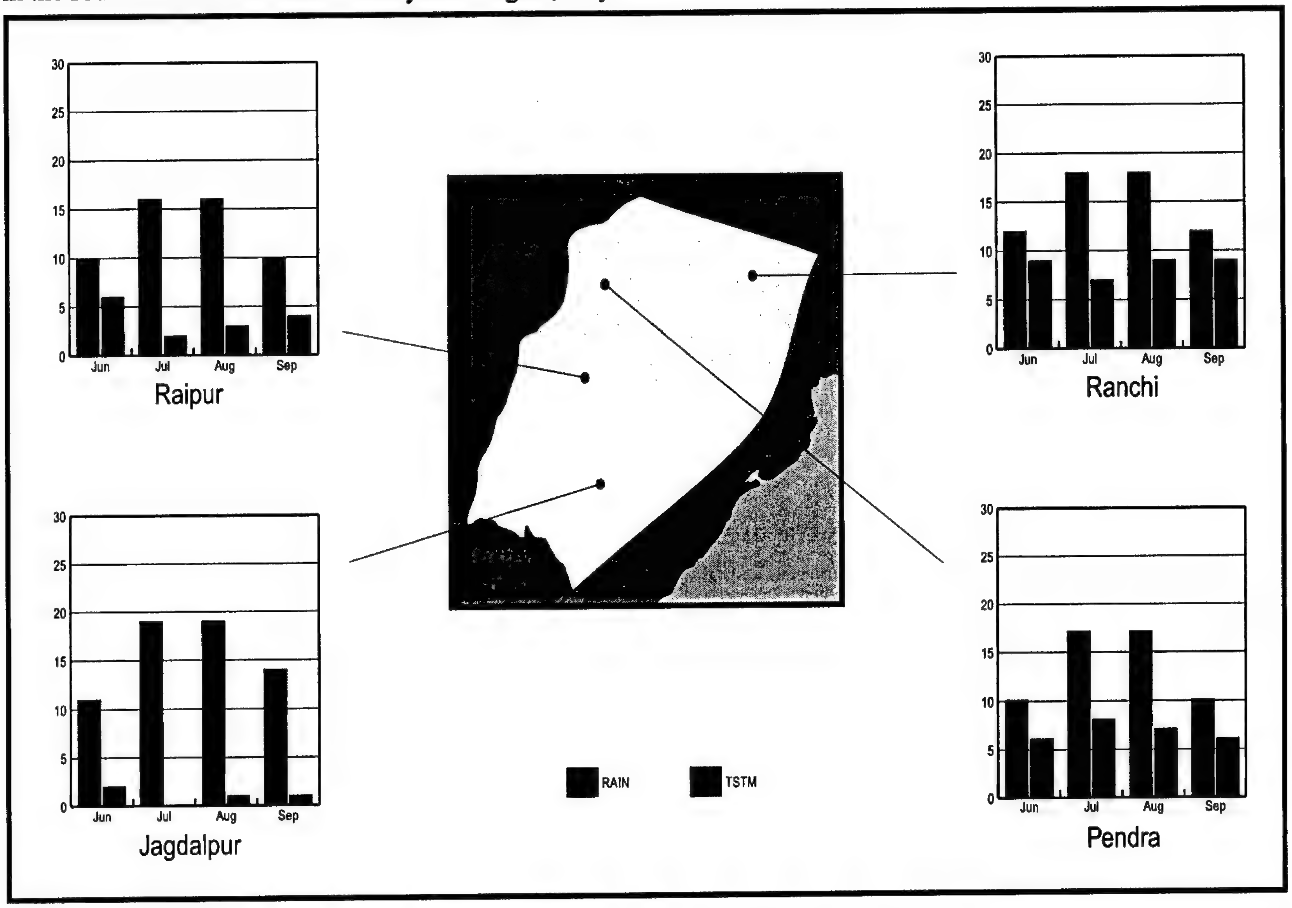


Figure 4-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures decrease from June to July as the cloudy skies and monsoon rains cool the earth, then remain relatively stable until the rains decrease in September. In June, the mean highs are 92° to 99°F (33° to 37°C); in July and August, the mean highs are 85° to 90°F (29° to 32°C). In September, they cool to 82° to 87°F (28° to 31°C). The mean lows in June are 75° to 80°F (24° to 27°C); in July through September, they are 71° to 79°F (22° to 26°C), August and September are slightly cooler than July. The farther inland a site, the higher the mean high and the lower the mean low. Figures 4-25 and 4-26 show the July mean maximum and minimum temperatures, respectively.

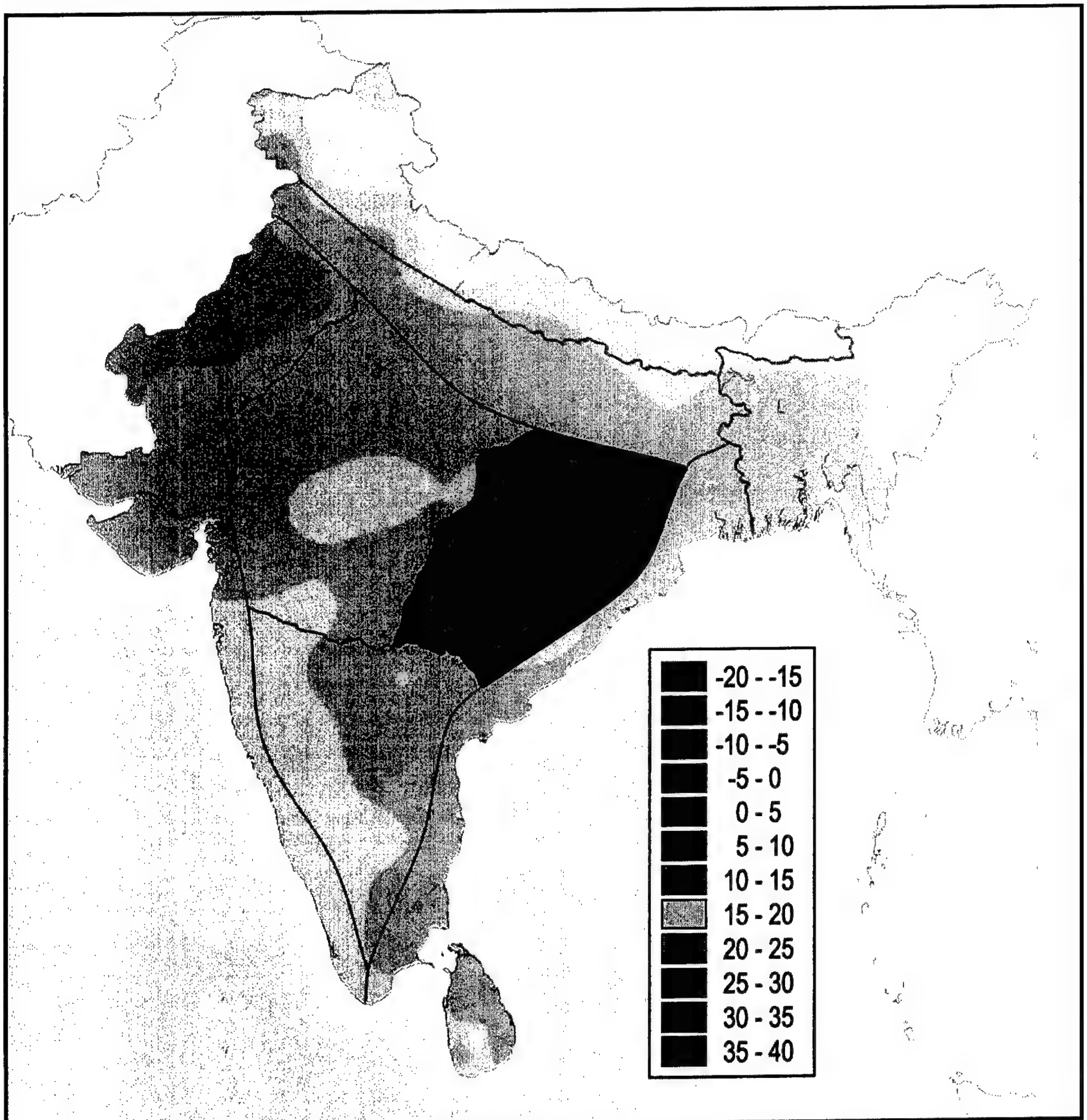


Figure 4-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher or low than the mean. Mean maximum temperatures during other months may be higher or lower, especially at the beginning and ending of the season.

The extreme highs are hottest in June, 107° to 117°F (42° to 47°C), and occur with drought conditions.The rest of the season, the extreme highs are 99° to 105°F (37° to 41°C). A powerful El Niño event, such as the 1997-1998 episode, can trigger prolonged periods of exceeding hot weather with extreme temperatures through the season of 115° to 122°F (46° to 50°C). The southwestern interior of this region is the most likely to experience these temperatures in an El Niño year. The extreme lows are 60° to 70°F (16° to 21°C), coolest in the highlands and warmest in the lowlands, throughout the season.

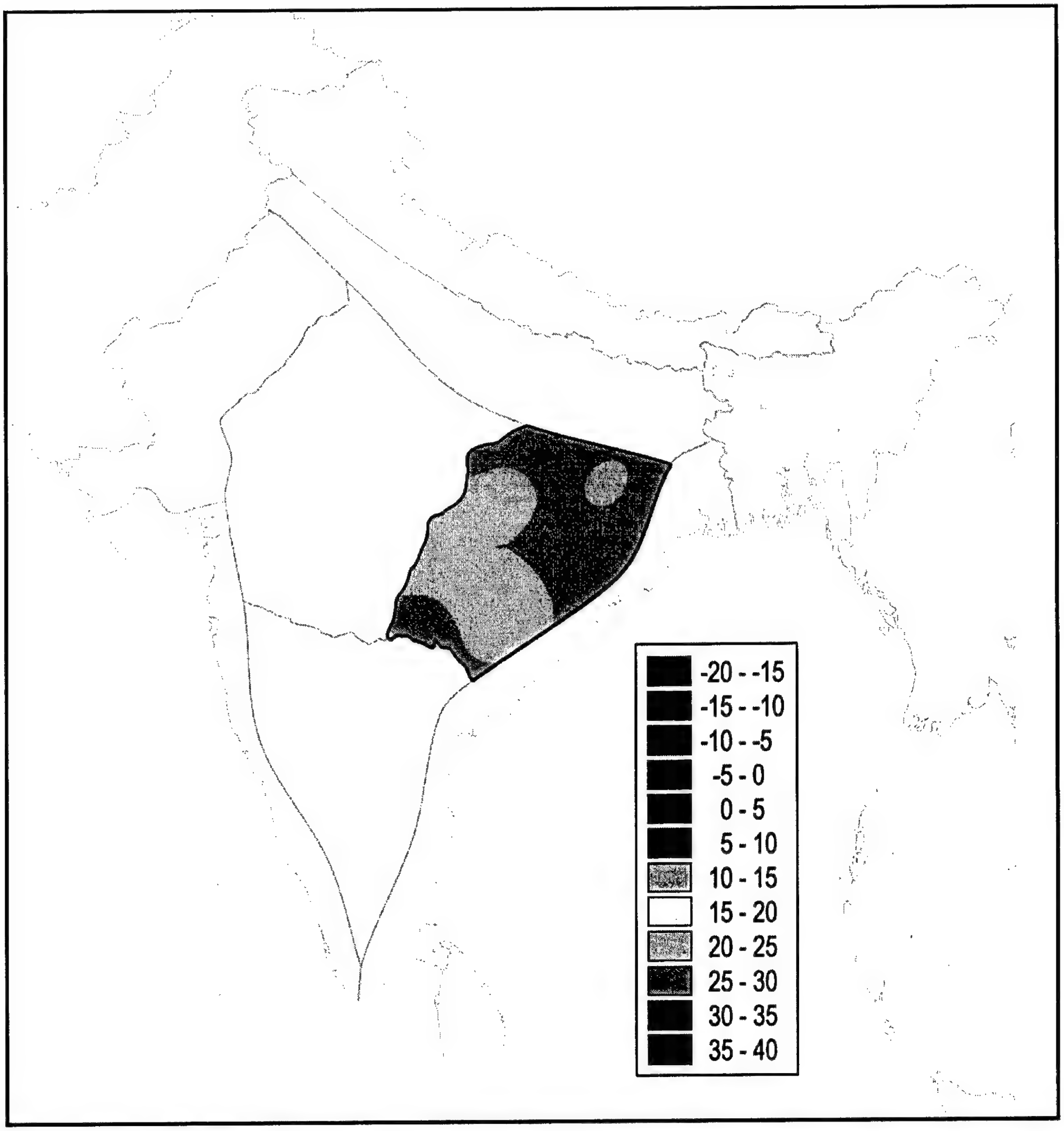


Figure 4-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during other months may be higher or lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. The rains of the southwest monsoon season end. The equatorial trough (ET) begins its retreat southward as the thermal low over Asia fades away. The withdrawal of the southwest monsoon occurs more slowly than the onset and can take 2 months to withdraw from the peninsula. The progression southward begins quickly then slows but is usually orderly. It occurs first in the northern-most part of the region; the ET is out of northern India by mid-October. It is south of the tip of the peninsula by late November or early December. Heavy rains accompany the ET as it moves through an area.

The equatorial westerlies, the Somali jet, and the tropical easterly jet, key elements of the southwest monsoon season, all disappear. The deep band of easterlies also retreats southward in this phase. By the end of November, it will be largely south of the peninsula. The thermal high of the Asiatic winter begins to form now, and wind flow at all levels is relatively ambiguous as a result. Because shear aloft is reduced in this transition season, this is when tropical cyclones have the best chance of developing and growing powerful. The Bay of Bengal is a favored breeding ground for tropical cyclones.

October and November are consistently more active tropical cyclone months than April and May. This is when Bay of Bengal water is warmest and storms reach maximum occurrence rates. These storms are not as powerful as open ocean storms, but they still carry heavy rains and strong winds. The mean storm track in this season is spilt. One branch directs storms to a landfall in the northeastern coastal area. The other directs them to the southern end of the peninsula just north of Sri Lanka.

By the end of November, the ET is south of India and headed south of the equator. General northeasterly flow is established by the end of November, and the induced leeside trough at the southern foot of the Himalayas starts to develop. This will provide a track for migratory lows out of Europe. Once the subtropical jet is established south of the mountains, lows will move through very quickly. Early season lows are not uncommon by mid-November. As northeast flow becomes established, onshore winds bring winter rains to the southeast coast of the peninsula as early as the end of November~~. Cloud cover associated~~ with this rain spreads inland to the windward slopes of the Eastern Ghats.

Sky Cover. The northern areas see the first decline in cloud cover in October and improvement progresses southward over the month. Cloud types are stratiform in the southwest monsoon air mass and much more cumuliform in the northeast monsoon air. Skies are clear to scattered by November in most of the area. The exception is the eastern slopes of the Eastern Ghats, where cloud cover averages 55-65 percent in onshore flow. Diurnally, the afternoon hours have the most cloud cover and the hours from midnight to 2-3 hours after sunrise have the least.

Ceilings below 5,000 feet occur 15-20 percent of the time in the lowlands and 25-30 percent of the time at higher elevations from 1-2 hours after sunset to 1-2 hours after sunrise. Figure 4-27 shows the percent frequency of ceilings below 5,000 feet from locations within the region. By mid-morning, the rates drop to 5-10 percent of the time in the lowlands and 15-20 percent of the time at higher elevations. The occurrence rates increase again from midday to sunset to afternoon maximums of 20-25 percent of the time in the lowlands and 35-40 percent of the time in the highlands. The southwestern and south central lowlands have the least cloud cover. The Eastern Ghats and the northern highlands have the most. Ceilings below 1,000 feet occur under 5 percent of the time at all hours in the Eastern Ghats and the northern highlands. In the lowlands, they occur only with convective precipitation and last only as long as heavy rain falls.

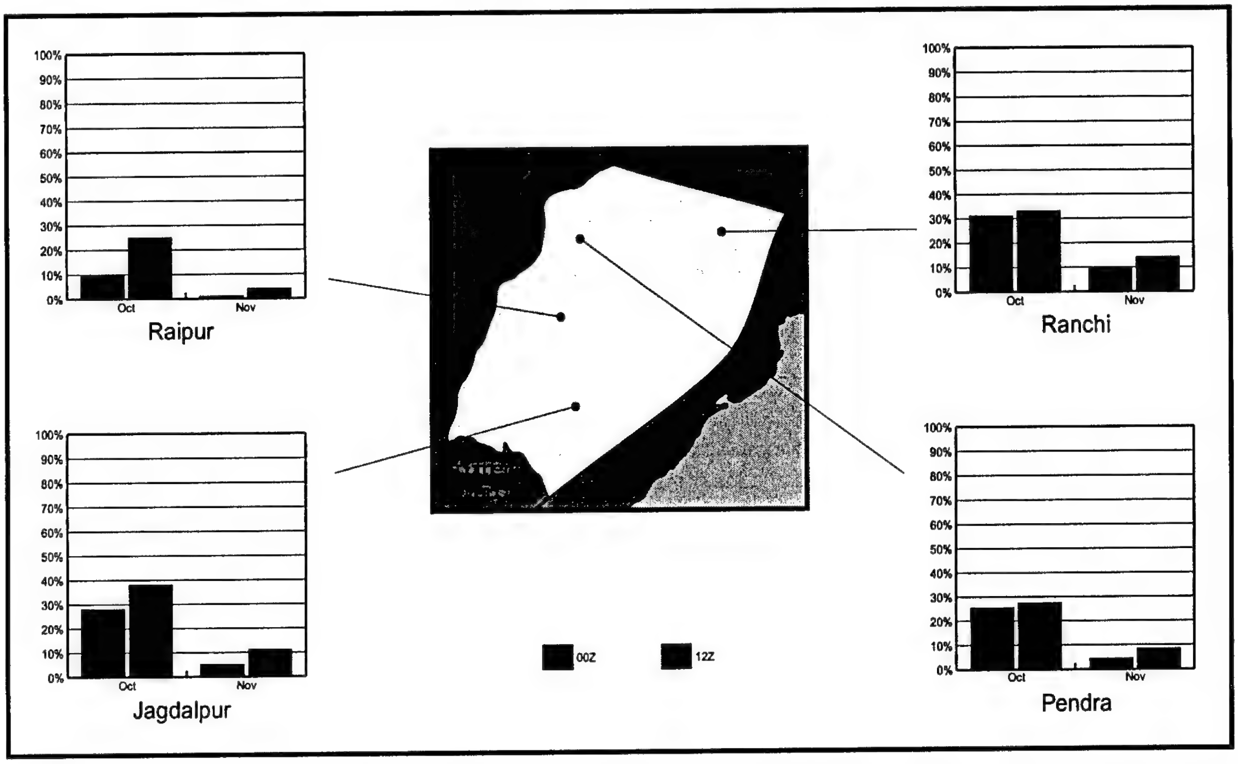


Figure 4-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is generally excellent. The rains stop early in the season, but the ground retains enough moisture through the rest of the period to resist dust development except in the most heavily trafficked areas. Even there, visibility will be restricted in limited areas right around the traffic. Morning fog dissipates quickly once the sun rises. Haze persists everywhere, but does not restrict visibility significantly. Urban industrial areas see deteriorating visibility in smog but no major restrictions.

Visibility below 2 1/2 miles (4,000 meters) occurs well under 5 percent of the time in the mornings in sunrise fog and almost never the rest of the day (see Figure 4-28). Visibility below 1 1/4 miles (2,000 meters) almost never occurs. It is most likely for short periods in heavy convective precipitation.

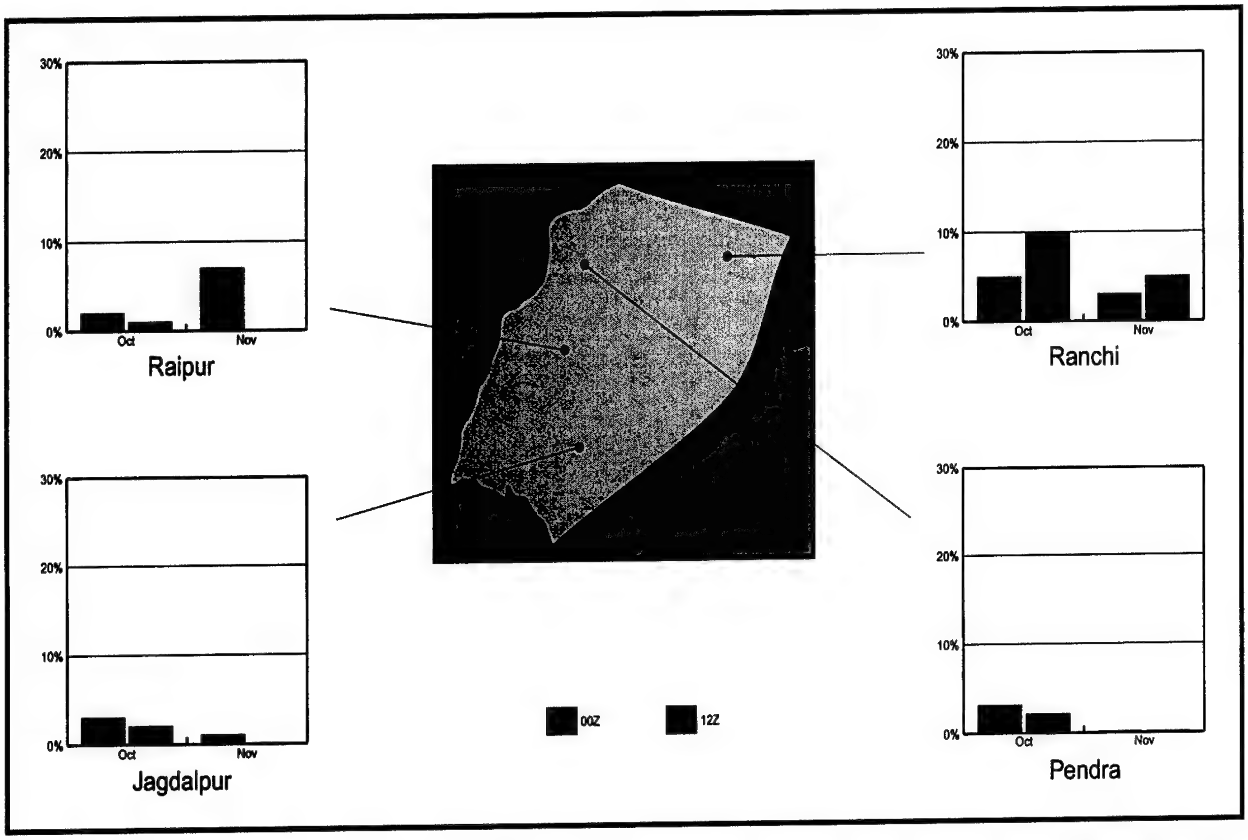


Figure 4-28. Post-Monsoon Percent Frequency of Visibility below 2 1/2 miles (4,000 Meters). The graphs show a monthly breakdown of the percent occurrence of visibility 4,000 meters based on location and diurnal influences.

Surface Winds. Winds become light and variable at generally under 5 knots as southwest winds are gradually replaced by northeasterlies. Figure 4-29 shows the mean October surface winds across the region. Calms overnight and in the early morning hours become more and more common as the season progresses. Afternoon lake breezes steadily weaken from summer maximum strength, and night land breezes are only felt near the largest lakes by the end of the season.

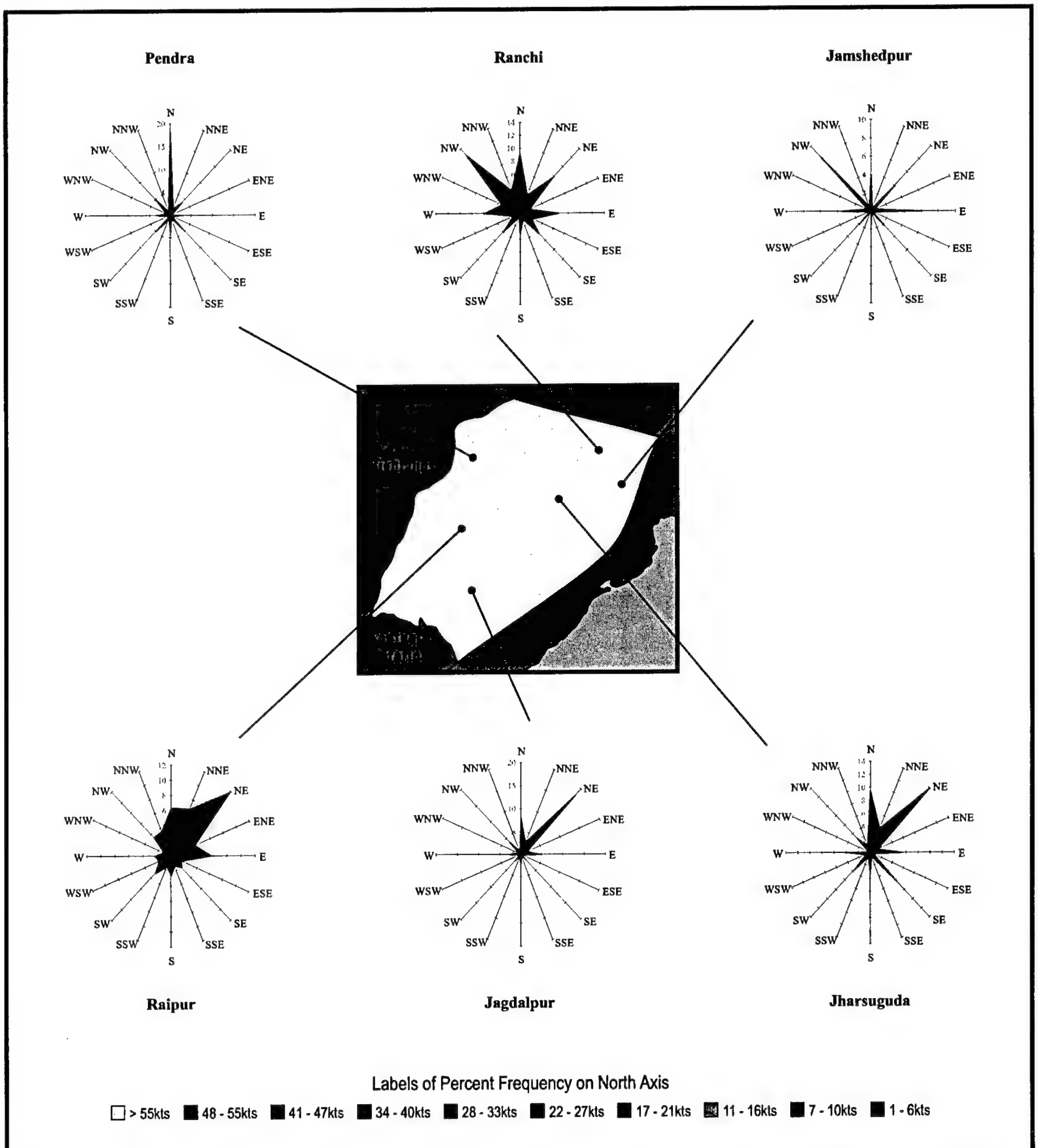


Figure 4-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The October 850-mb winds are from the northeast at 10 knots. In November, the 850-mb winds are from the northeast-southeast at 10 knots. The 700-mb winds are easterly at 5-10 knots in both months. The 500-mb winds are from the east at 10-15 knots all season. At 300 mb, easterly winds at 10 knots in October give way to southwesterly winds at 10 knots in November. Figure 4-30 shows upper-level winds for Jagdalpur.

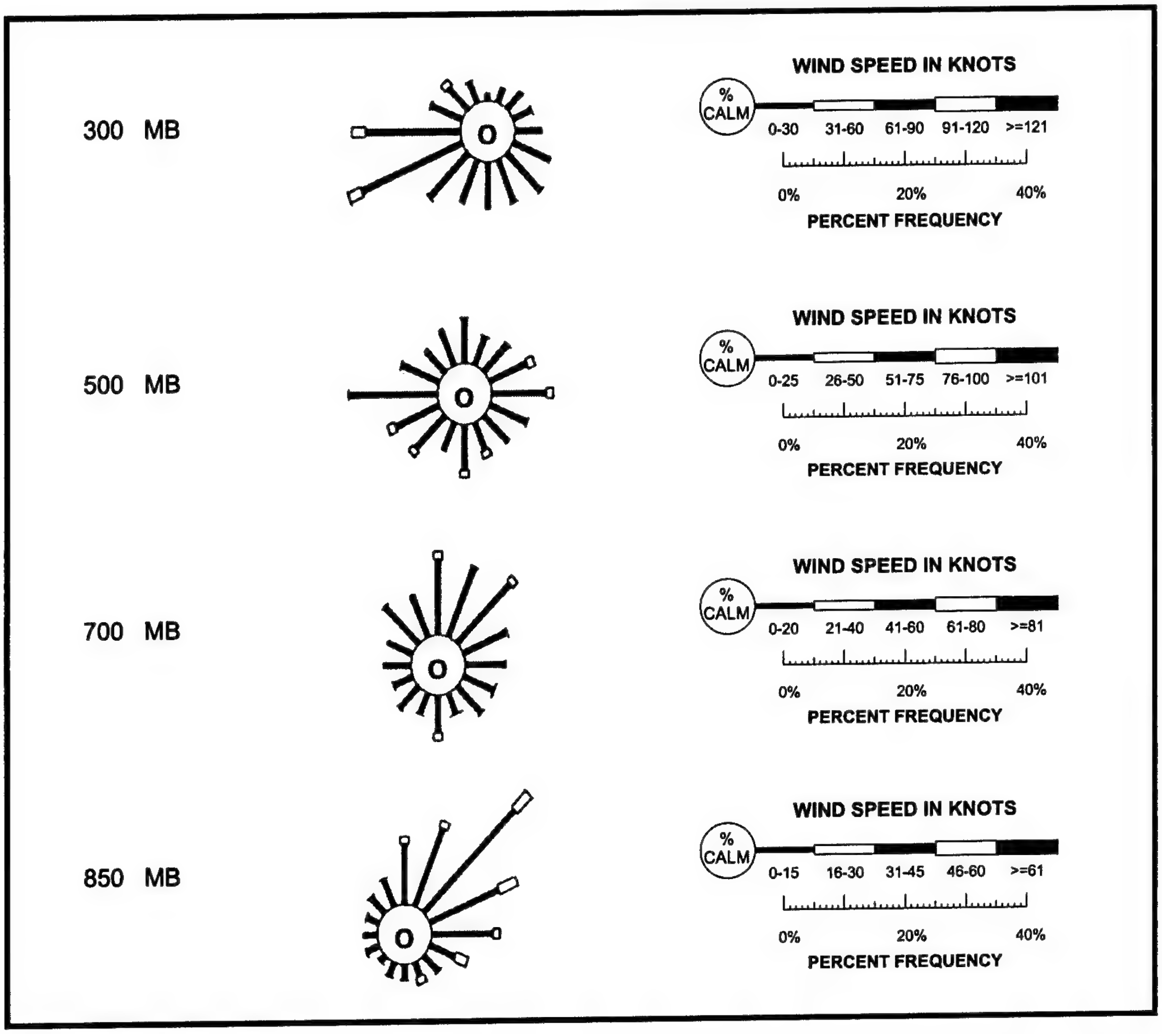


Figure 4-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Jagdalpur.

Precipitation. Rain decreases from October through November, and in both months, amounts are higher close to the coast than in the interior. During October, most places in the eastern third of the region get 5.5-7 inches (140-178 mm) of rain while locations deeper in the interior get 2-4.5 inches (51-114 mm) as noted in Figure 4-31. November rain is light almost everywhere, 0.5-1.5 inches (13-38 mm), except for the eastern slopes of the Eastern Ghats in the southern third of the region as the monsoon trough moves southward. There, as much as 12-15 inches (305-381 mm) of rain falls in November. The rest of the windward Eastern Ghats have 6-8 inches (152-203 mm) of rain in October and drop off to under one inch (25 mm) by November. The amount is smallest in the northern near-coastal areas and greatest in the southern near-coastal areas.

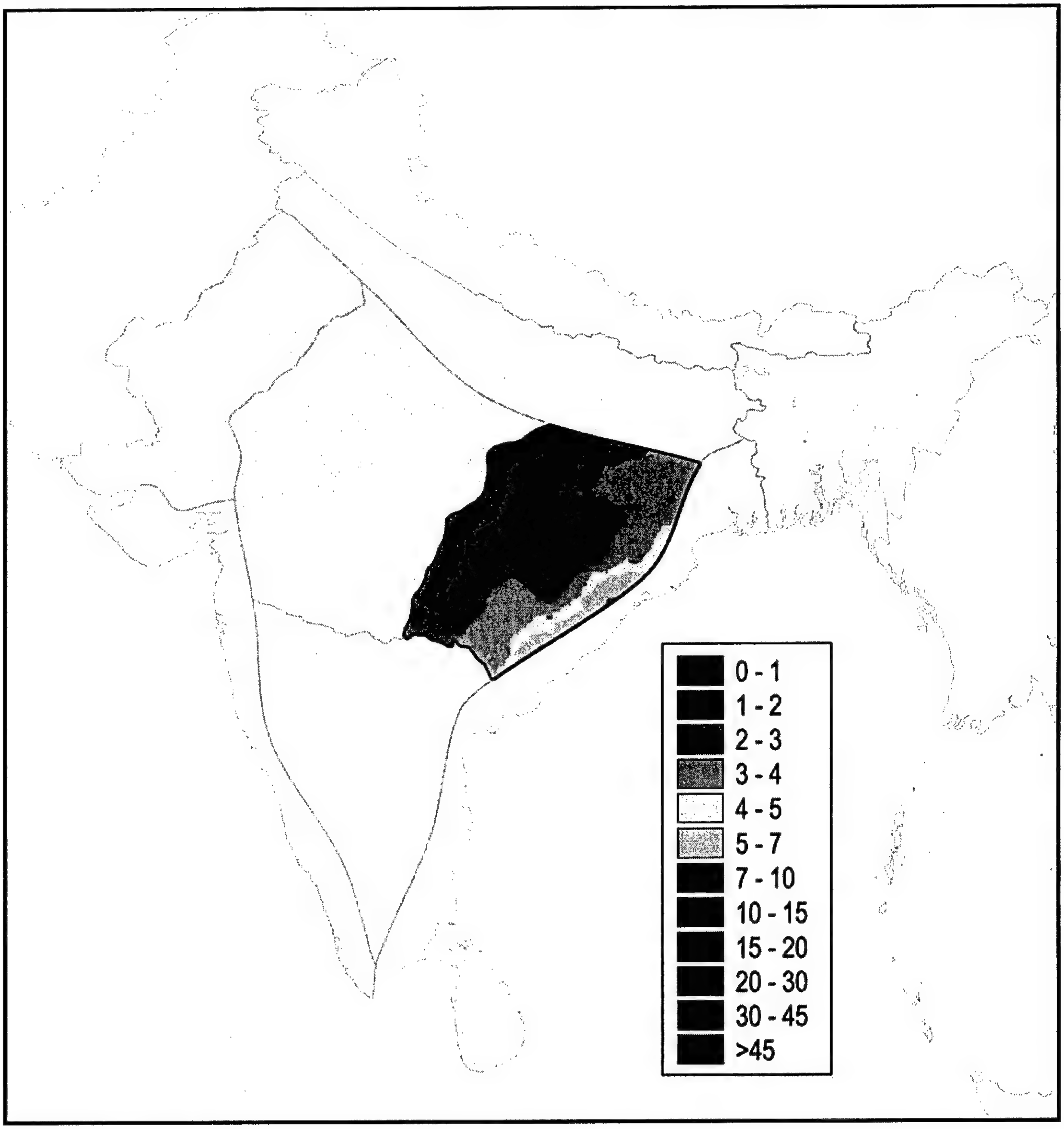


Figure 4-31. October Mean Precipitation (Inches). The figure shows mean precipitable water amounts in the region.

Rain falls on 3-6 days in October (see Figure 4-32) and one day or less in November. The windward slopes in the northeast and in the Eastern Ghats have a slightly higher rate, 5-8 days in October and 2-4 days in November. Thunderstorms are at the end-of-year maximum in September and October with the southwest monsoon as it moves south out of the area. Thunderstorms occur 1-3 days in October and less than one day in November. The windward slopes of the northeastern highlands and the Eastern Ghats have a slightly higher rate in October of 4-5. By November, the rate drops to below one day per month (winter convective storm occurrence rates).

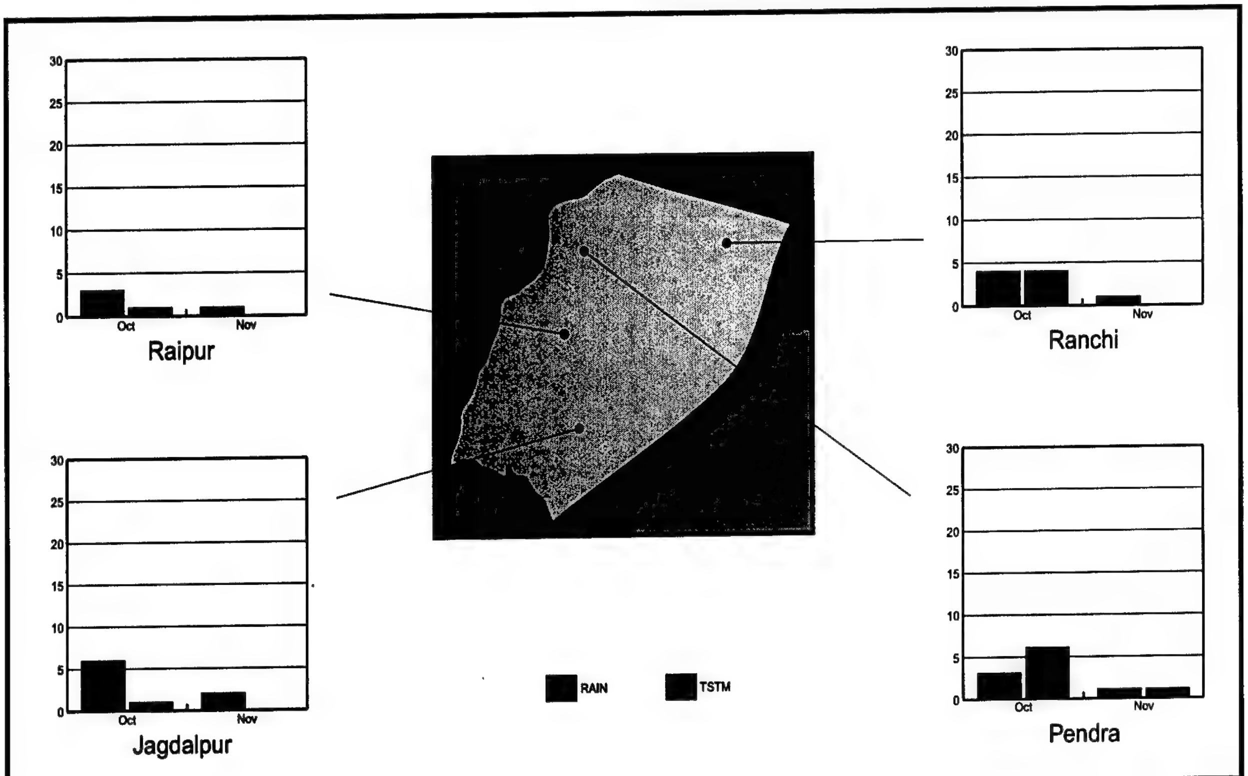


Figure 4-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. October is warmer than November everywhere. Figures 4-33 and 4-34 show the respective October mean maximum and minimum temperatures.In October, the mean highs are 83° to 90°F (28° to 32°C), and the mean lows are 64° to 77°F (18° to 25°C). Temperatures are warmer inland than near the coast. In the lowlands, the October mean highs are 88° to 92°F (31° to 33°C); in November, they cool to 80° to 85°F (27° to 29°C). Typically, the interior stations have wider diurnal temperature ranges (warmer high and cooler low temperatures) than those closer to the coast because the relative humidity is generally lower. Temperatures also cool adiabatically with elevation. Most reporting stations in the highlands report mean highs of 82° to 85°F

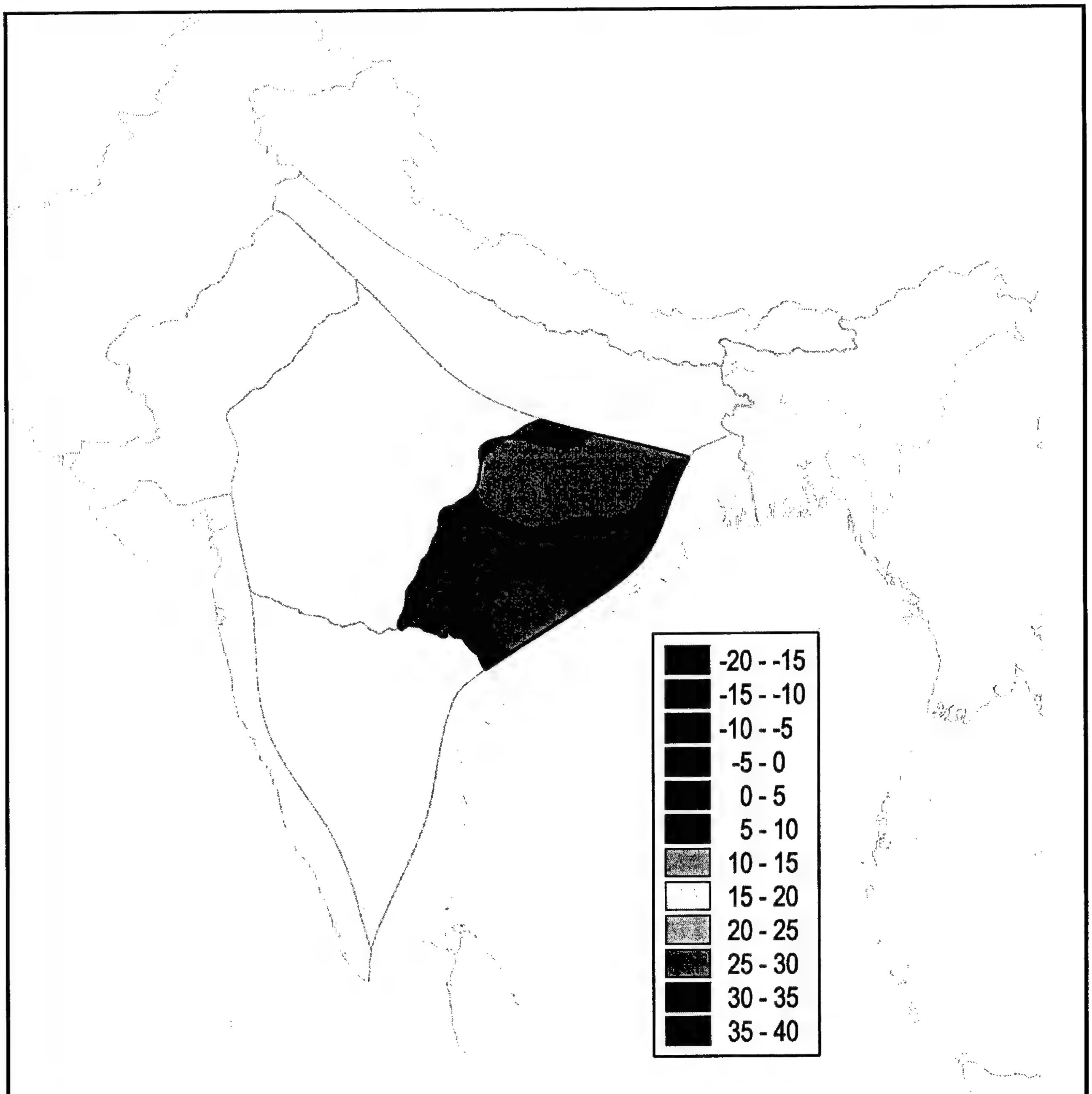


Figure 4-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for October. Daily high temperatures are often higher or lower than the mean. Mean maximum temperatures during November may be lower, especially at the end of the month.

in October and 75° to 78°F (24° to 26°C) in November. The October mean lows are 70° to 75°F (21° to 24°C) in the lowlands and 64° to 68°F (18° to 20°C) in the highlands. By November, they cool to 61° to 67°F (16° to 20°C) in the lowlands and 52° to 59°F (11° to 15°C) in the highlands. The extreme highs are 93° to 101°F (34° to 38°C) in October and 89° to 97°F (32° to 36°C) in November. The years of drought (often associated with El Niño events) are most likely to have the extremely high temperatures. The extreme lows are 52° to 57°F (11° to 14°C) in October and 39° to 44°F (4° to 7°C) in November. These record lows are linked to cold outbreaks and are most likely in the northern third of the region.

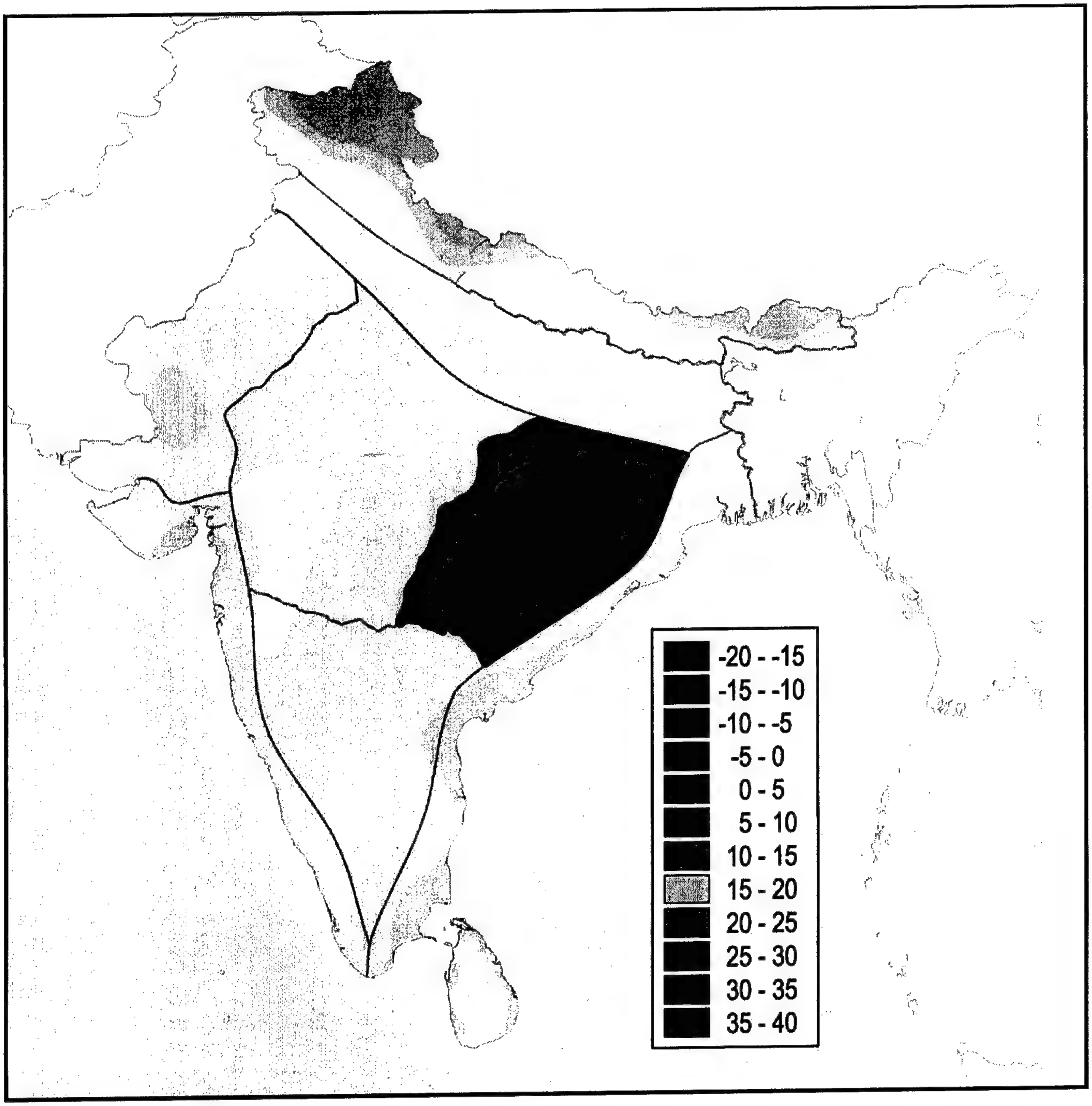


Figure 4-33. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for October. Daily low temperatures are often higher or lower than the mean. Mean minimum temperatures during November may be lower, especially at the end of the month.

Continental South Asia

Chapter 5

NORTHWEST INDIA

This chapter describes the geography, major climatic controls, special climatic features, and seasonal weather for Northwest India.

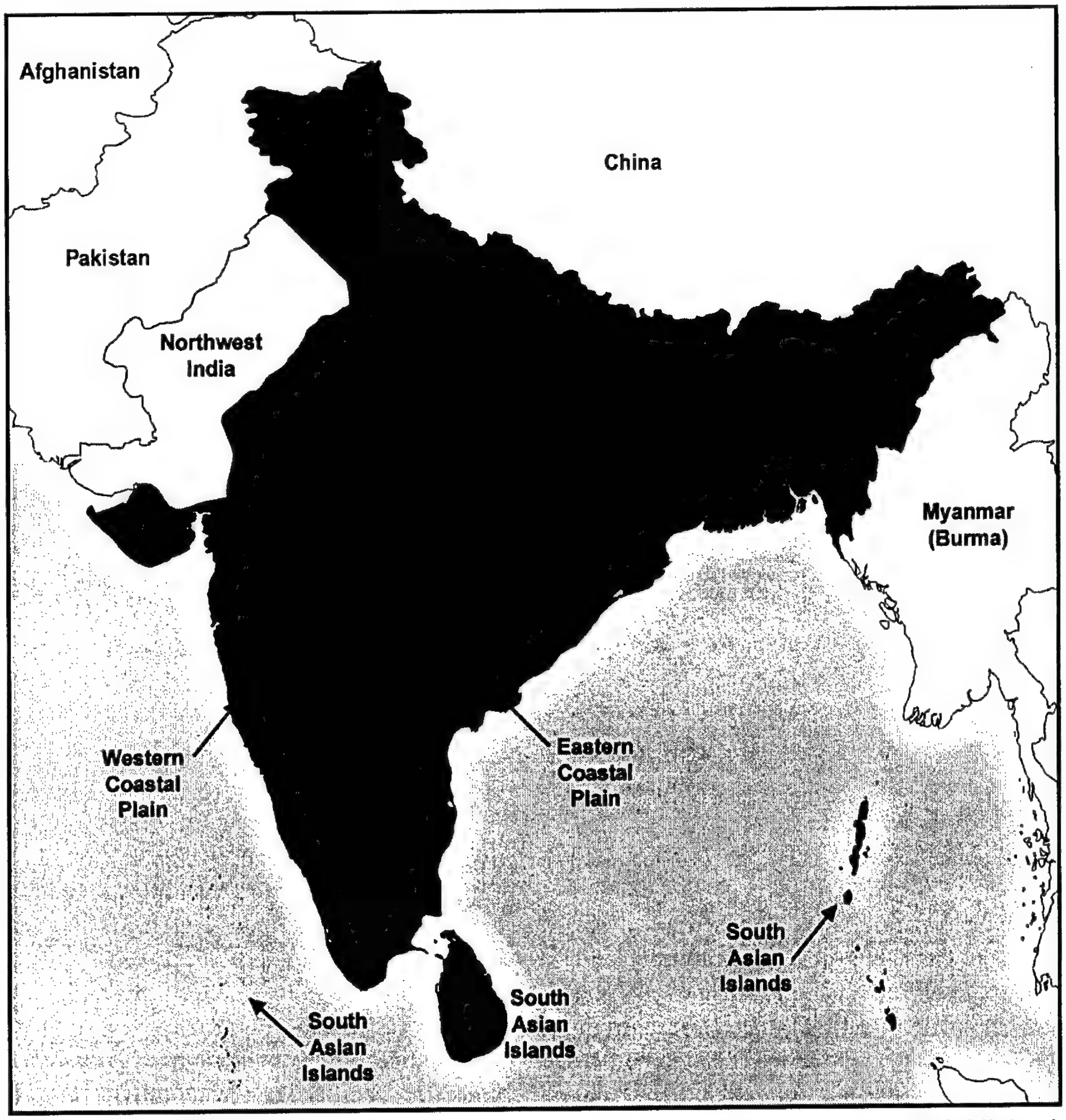


Figure 5-1. Northwest India. This figure shows the location of Northwest India (highlighted in yellow) in relation to the other South Asia zones.

List of Topics

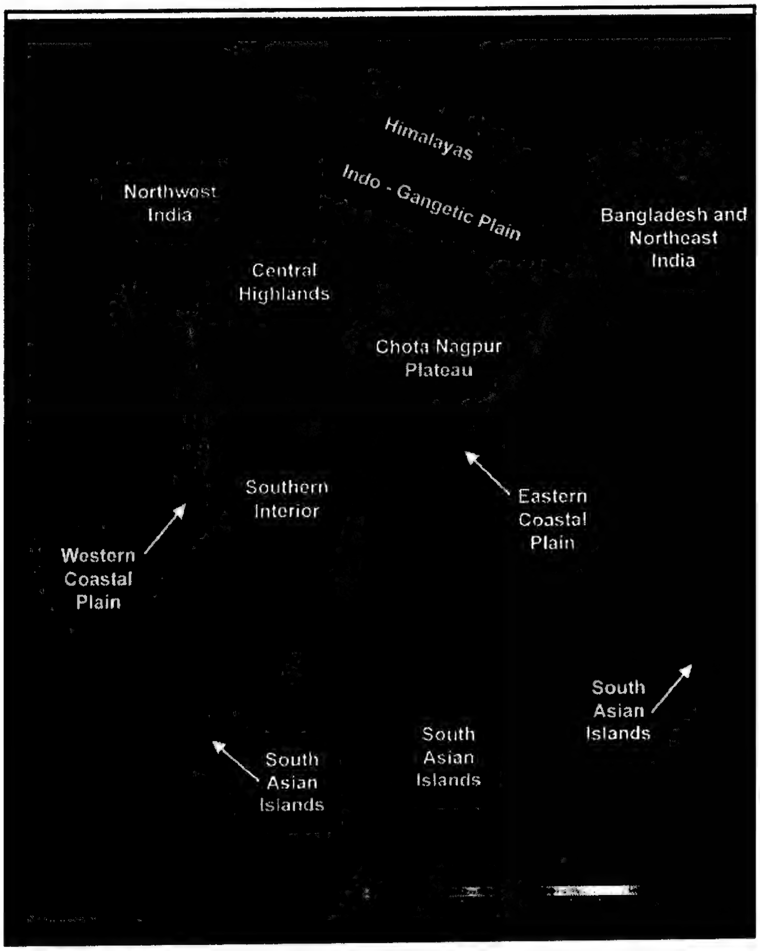


Figure 5-2a. Topography of Northwest India.

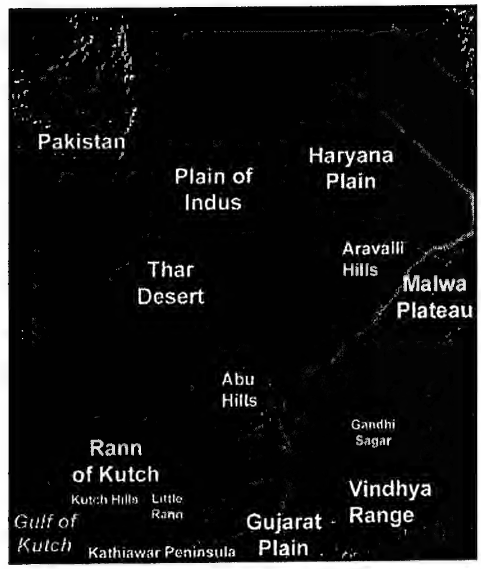


Figure 5-2b. Expanded View of the Topography of Northwest India.

Topography

Boundaries. Northwest India is composed mostly of the Thar Desert. The Thar lies in both India and Pakistan, with roughly half in India. In the east, the average elevation is 1,000 feet (300 meters), but drops to 500 feet (150 meters) near the India-Pakistan border. The Thar is crisscrossed by short, dry stream beds and is characterized by stable sand dunes that alternate with rocky outcrops along the swales. Transverse dunes lie perpendicular to the prevailing wind direction. Northeast-southwest oriented dunes predominate near the Rann of Kutch. They average 30-50 feet (10-15 meters) high, 3-9 miles (5-10 km) long, and 500-650 feet (150-200 meters) wide.

Major Terrain Features. The Aravalli Hills separate the desert of the west from more fertile Central Highlands of the east. Mount Abu, at 5,650 feet (1,722 meters), is the highest peak of the Aravalli. The Luni River, the only significant river in northwest India, rises in Pushkar Valley of Ajmer and flows 200 miles west-southwest into the Rann of Kutch.

The Gulf of Kutch, an inlet of the Arabian Sea, meets the northwest coast of the Kathiawar Peninsula. A salt desert called Little Rann encircles Kutch on the north and east. The hills of Kutch are divided into 3 groups, the hills of Kutch, Vagad in the east, and the Rann Islands in the north. Nearly all the ranges and many of the hills are steep, scarped on the north slopes and gently sloped towards the south. In Kutch proper, the hills are widely scattered in the west then gradually narrow eastward into a single range. Dhinodhar, a volcano in Kutch, is 1,000 feet (300 meters) above the Rann. Of the hills that rise out of the Rann, Pachham, 1,411 feet (430 meters), is the tallest.

Rivers and Drainage Systems. Most Kutch rivers are seasonal features. They generally flow in the

southwest monsoon and dry up over the winter. Rising in the central uplands they flow either north to the Rann of Kutch or south to the Gulf of Kutch. Aside from seasonal rivers, the Sabermati in the east, the Luni in the northeast, and Kori Creek in the west carry very the little water flow through Kutch to the sea.

Major Climatic Controls

Asiatic High. This thermal high, also called the Siberian high, develops over Asia and dominates the weather over the entire continent from November to April. The vast pool of cold, dry air it pushes outward in all directions is a key part of the northeast monsoon in south Asia. Because of the continental source of the air, the weather is dry. The leeside trough on the southern side of the Himalayas created by flow out of this high provides a track for storms that move out of Europe on the subtropical jet.

Australian High. This thermal high sets up over Australia during the Southern Hemispheric winter (May through October). It helps smooth the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season in south Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon. This high, which forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area, influences the tracks of low-pressure systems depending on its strength and position. Although typically weak, when the high is at its strongest, it tends to block low pressure systems from the track across the southern foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe that ride the subtropical jet to move rapidly across northern India.

North Pacific High. This is a major player in the monsoon seasons of South Asia. It shifts north and west in the Northern Hemisphere summer (May through October) and east and south in the winter (November to April). The high is linked to the position of the ET, which, in turn, marks the boundary between the northeast and southwest monsoons.

South Indian Ocean (Mascarene) High. This year-round high-pressure system shifts north and south with the sun. At its strongest during the Southern Hemisphere winter, it provides cross-equatorial flow from May to October (reflected in both the Somali jet and the equatorial westerlies). This warm, moist flow contributes significantly to the ET shift to the north, which brings the southwest monsoon (and rain) to South Asia.

Asiatic Low. This is a thermal low that replaces the Asiatic high during the Northern Hemisphere summer. The land heats, and the consequent low draws in air. This contributes to the ET shift northward, which brings the southwest monsoon flow to South Asia.

Australian Low. This is a thermal low that develops over Australia during the Southern hemisphere summer. It breaks up the smooth outflow of the South Indian Ocean high and the South Pacific high. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the area of the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has both a distinct rainy season and a dry season. Under the northeast monsoon (November to April), the region is largely dry. Under the southwest monsoon (May though October), it is rainy. Onset of the rainy season varies by latitude and terrain, but it usually occurs between mid-May and late June. Duration of the rainy season also varies widely. In the north, the southwest monsoon season is short. In the far south, it lasts twice as long as in the far north.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north, the southwest monsoon takes over in South Asia. When it shifts south, the northeast monsoon assumes control. Chapter 2 offers more details.

Bay of Bengal. This large bay is the primary breeding ground for tropical cyclone storm systems that affect this region. Most of the rainfall in this area occurs from storms that develop or refire over this body of water along the ET, the India-Myanmar trough, or from other mechanisms. The northern half of the bay is more active than the southern half, but storms develop here year-round. The most active times are in October-November (maximum activity) and April-May (secondary maximum). Storms tend to come ashore on the east coast of the peninsula then recurve northward.

Special Climatic Controls

Tropical Easterly Jet (TEJ). This jet exists only during the southwest monsoon season. An upper-level jet that overlays the low-level westerlies, it provides an outflow mechanism for disturbances that develop below it. The heaviest precipitation in South Asia occurs directly beneath the TEJ. The Bay of Bengal and the Arabian Sea are both under the TEJ. The Bay of Bengal is well known to be a prime area for the development or regeneration of monsoon depressions, tropical cyclones, tropical waves, tropical vortices, and mesoscale convective complexes. The TEJ is an important element in the process.

Somali Jet (Low-Level Jet). Also known as the East African low-level jet, this jet exists during the southwest monsoon season and is a key transport for air from the Southern Hemisphere into the Northern Hemisphere. It has been suggested 50 percent or more of the cross-equatorial flow from the Southern Hemisphere into the Northern Hemisphere is moved by this jet. It is created when outflow from the South Indian Ocean high flows toward the thermal low pressure over northern Africa. The western edge of the outflow air mass piles up against the eastern slopes of the high mountains of the eastern African coast. The result of this squeeze is a terrain-induced zone of tight pressure gradient and the jet develops there. The Somali jet is a key element in the development of the equatorial westerlies that dominate the southwest monsoon season.

Equatorial Westerlies. These winds exist during the southwest monsoon season. These large-scale, low-level winds are a result of a combination of factors. Outflow from the South Indian Ocean high (from the southeast) flows toward the thermal low over northern Africa (to the northwest), but the high mountains on the eastern coast of Africa are significant barriers that force a deflection. The Somali jet then helps transport the air into the Northern Hemisphere. The air mass is recurved eastward and these westerly winds take over throughout the monsoon region.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season when its southern branch slips south of the Himalayas. Low-pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and Northeast India. During the southwest monsoon, the STJ is north of the Himalayas.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter, several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move theses waves into and through the area.

Tibetan Anticyclone. This Northern Hemisphere (southwest monsoon) upper-air feature sets up in the zone between the deep easterlies that reach almost to the foot of the Himalayas by July and the deep westerlies of the Northern Hemisphere mid-latitudes. Formed above the thermal low of the Tibetan plateau, it is important to the climate during this season because

tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought. For a more detailed descriptions, review Chapter 2.

Tropical Easterlies. This deep east wind band persists year-round in the low latitudes. It shifts north and south with the sun. During the southwest monsoon, it shifts north and widens to encompass a larger area. Thanks to a number of factors, it also strengthens enough to develop the tropical easterly jet, a broad ribbon of higher winds that strongly influence the development of monsoon rains, tropical disturbances of all intensities, and monsoon depressions. During the northeast monsoon, the band of easterlies narrows and shifts south. At the height of the northeast monsoon, the easterlies are held south of 5° N.

Monsoon Depressions/Low-Pressure Systems. These are important synoptic-scale disturbances that make major contributions to the monsoon circulation in organizing low-level convergence. During the southwest monsoon season, these storms move along the ET toward the north. They normally form in the Bay of Bengal north of 18° N and move west-northwest across India. They bring heavy rains, especially in the southwest quadrant of the storm. These systems rarely develop into tropical cyclones and are associated with a series of low-pressure systems and easterly waves in the northern Bay of Bengal. The strongest winds are in the southern sector of the storms thanks to augmentation by the equatorial westerlies. Approximately 80 percent of the total number of depressions that form in the South Asia region are monsoon depressions. The majority of monsoon depressions and other cyclonic storms form in the Bay of Bengal as opposed to the Arabian Sea and most of them form in the northern part of the bay.

Easterly Waves. During the southwest monsoon season, easterly waves are known to help fire the formation of monsoon depressions over the northern Bay of Bengal. They travel from east to west in the deep easterlies and last 1-2 weeks. They are accompanied by clear weather ahead of the trough and heavy showers and thunderstorms behind. They sometimes create cyclonic vortices off shore the southwestern end of the Indian peninsula and can cause thunderstorms and rainshowers over Sri Lanka and the southern tip of the peninsula. The intensity and frequency of occurrence of easterly waves are indicators of the strength of the monsoon.

Mid-Tropospheric Cyclones. Mid-tropospheric cyclones develop during the southwest monsoon near the 600 mb level. They occur most frequently in the northeastern Arabian Sea and are a major producer of rain on the west coast plains of India. A weak trough along the northwest coast is often the only indication of a surface disturbance. The cyclones produce widespread layered clouds, imbedded thunderstorms, and heavy precipitation--8 inches (203 mm) in 24 hours. The systems last 9-10 days and are essentially stationary.

Land/Sea Breeze. These winds are caused by diurnal land/sea temperature differences. By day, the sea is cooler than land and the wind blows onshore. By night, the temperature difference reverses and the winds become offshore. Onshore winds produce cloud cover and convection over land. During the southwest monsoon, sea breeze winds are augmented by the large scale flow and reach far inland, as much as 100 miles (160 km). This brings moist air well inland to rise up mountain slopes and cause precipitation in the mountains. Off shore winds clear the skies over land by pushing cloud cover out to sea. These same winds can slide convection that developed over the mountains down into the lowlands between them and the sea. Depending on the steepness of the slopes, the downslope flow can create a "front" that fires thunderstorm activity all along the convergence zone between the cool mountain air and the warmer, moist air of the sea. This makes up a line of thunderstorms that marches to the sea over the lowlands.

Turbulence. Under the clear to scattered skies of winter and the hot season, turbulence caused by intense surface heating may extend up to 10,000 feet. The turbulence is usually light-moderate but can reach the severe category. Some low level turbulence is almost always present during the afternoons, but is most likely during the hot-weather season and with thunderstorms. Convection currents are most pronounced between 1000 and 1700 local. During the southwest monsoon, turbulence is primarily associated with convective currents and thunderstorms; during the winter months, turbulence is mostly with frontal systems. Moderate to severe turbulence occurs with the STJ at 35,000-40,000 feet during the winter and hot seasons. During the southwest monsoon, moderate to severe turbulence occurs near the TEJ at 40,000-45,000 feet.

Aircraft Icing. The mean height of the freezing level is 16,000-18,000 feet year round. The mean height of the -20° C isotherm is 26,000-28,000 feet all year. During the winter and hot season, there are very few clouds so there is little threat from icing. In clouds, especially during the southwest monsoon, moderate to severe icing is very likely at 16,000-28,000 feet.

Tropical Cyclones. Tropical cyclones occur any month of the year, but are least frequent from January through March. In April and May, these storms are still relatively infrequent, but those that do appear are apt to develop and become severe. Arabian Sea storms, on rare occasions, recurve northeast and strike the Rann of Kutch coast and move into the region to cause widespread devastation in heavy rains and floods. At the height of the southwest monsoon, a series of lows form in the Bay of Bengal and travel westward or northwestward over land. They sometimes die out over the interior, but reactivate over north-central India where they meet the fresh monsoon air from the Arabian Sea.

Thunderstorms. During the winter and early hot season, thunderstorms develop along the cold fronts that often accompany western disturbances as they move across northern India. All of these storms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does, it is usually small, soft, and causes little damage. Thunderstorms also accompany the ET.

Flooding. Incredible amounts of rain fall in a very short period of time during the southwest monsoon. Streams and rivers overflow their banks and fill the valleys. Flash floods occur quickly with little or no warning.

Heat. High temperatures and humidity create a wide variety of heat-related physical problems. The wet-bulb globe temperature (WBGT) averages 80° in January, and increases to greater than 90° by July.

Tropical Disturbances/Depressions. Tropical disturbances occur any month of the year, but are least frequent from January through March. In April and May, these depressions are still relatively infrequent, but those widespread devastation with wind, storm surge, heavy rain, and flood. At the height of the southwest monsoon, a series of lows form in the Bay of Bengal and travel westward or northwestward over land. They sometimes die out over the interior, but reactive over northwest India where they meet the fresh monsoon air from the Arabian Sea.

Dust Storms. Dust storms are common throughout northwest India. Strong, convective air currents created by intense surface heating lift the dry soil as high as 10,000 feet. Migratory systems that cross northern India from the west carry the dust to 25,000 feet or higher. In Ganganagar, dust and sand storms generally occur 27 days each year and in Bikaner, 18 days. In the northwest, these storms occur most frequently in June, and in the south and southeast in May.

Winter

General Weather. The Asiatic high, an intense, shallow, thermal high, dominates Asia. High pressure extends southwestward to Afghanistan and to the northwestern portions of India. The general movement of air is from a northerly direction. Because of the Himalayas, the air that crosses into India in winter comes from Afghanistan, from the southern slopes of the Himalayas and from the northeast around the eastern end of the massif. The predominant air mass over northern India during winter is continental polar with modifications from its long trajectory. A ridge of high pressure covers the northwest region in winter; this acts as a secondary source region of the polar air during this season. During winter, the Thar Desert is under the influence of western disturbances. These systems, traveling from west to east on the STJ, occasionally produce cloudiness and light rain over the region. Overall, the climate is dry with clear skies, intense heating, and high daytime temperatures with a large diurnal temperature range.

Sky Cover. Predominantly clear skies are broken only occasionally by western disturbances. Middle and high clouds are the main features. Along the coast, there is very little variation of cloudiness, although there might be a slight increase in the early morning and a decrease in the evening. Over the interior, cumulus clouds sometimes develop during the afternoons, then dissipate by sundown. In the early morning, particularly over the river valleys, low stratus may occur but will rapidly burn off after sunrise. Low ceilings are infrequent. Ceilings less than 5,000 feet occur less than 3 percent of the time at most places and are generally more frequent in the morning than afternoon (see Figure 5-3). Ceilings less than 1,000 feet rarely occur at all. The most frequent low cloud bases are at 3,000-6,000 feet but even these are uncommon.

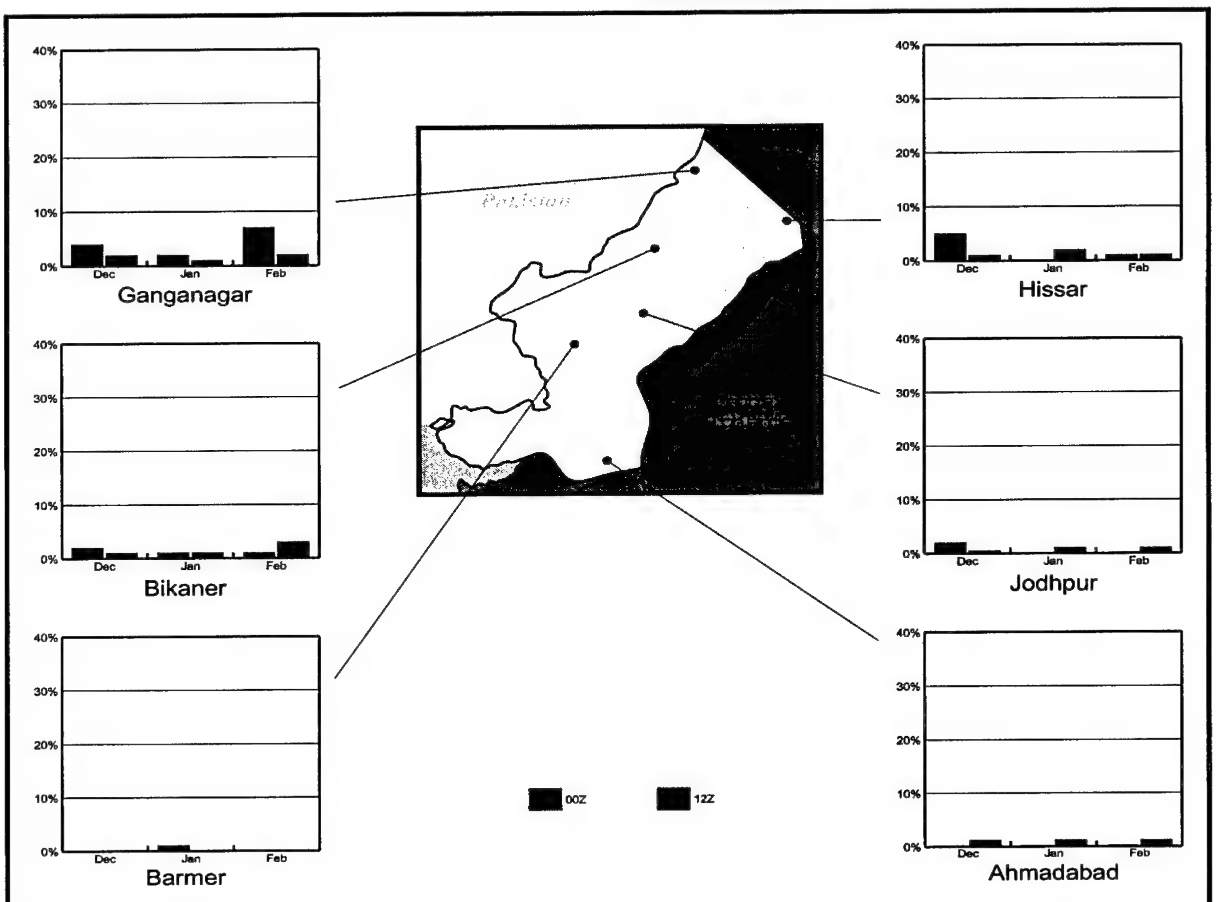


Figure 5-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. In general, visibility is worst during the hours near sunrise and best during the afternoon. Diurnal variation is much greater during winter than in any other season. Fog is the most frequent in winter as a result of radiational cooling. The height to which fog extends varies from shallow ground fog to about 1,000 feet (300 meters) in upslope fog along the Aravalli range. The highest frequency for fog occurs along the Aravalli Range. Radiational fog usually occurs there in the early morning hours and dissipates by mid-morning, with an average duration of 3-5 hours. Rain and/or drizzle, although infrequent, do occur. Larger cities are usually surrounded by areas of low visibility that results from pollution. Smoke haze is worst at night and early mornings. A mixture of smoke and fog is common in the morning hours in industrial cities. Dust storms are very infrequent in winter. Visibility less than 2 1/2 miles (4,000 meters), as shown in Figure 5-4, occurs 5-7 percent of the time throughout the region. Occurrences of visibility less than 4,000 meters around major industrial centers increases to 7-10 percent of the time. Visibility less than 1/2 mile (800 meters) is rare throughout the region.

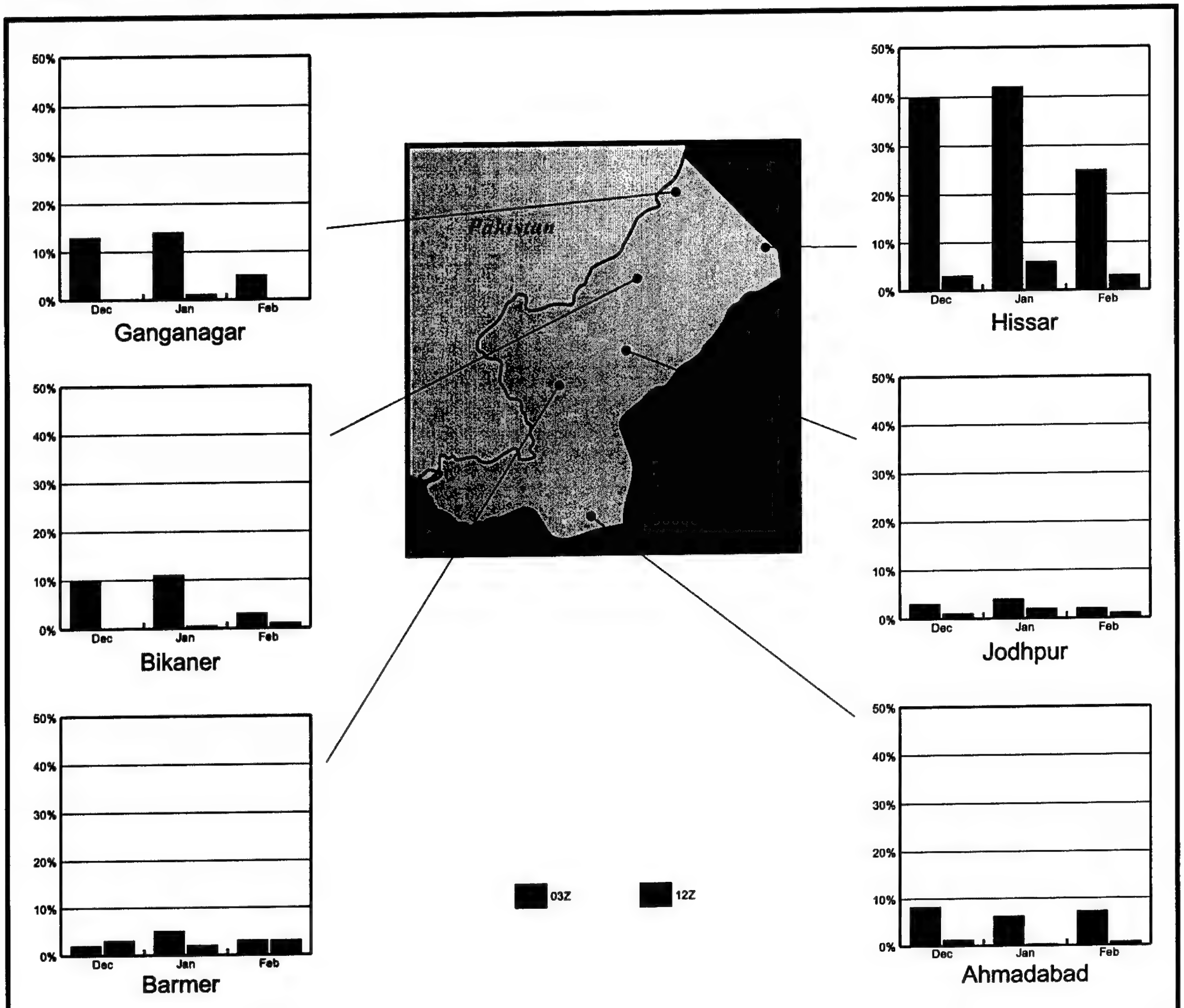


Figure 5-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,800 meters based on location and diurnal influences.

Surface Winds. The prevailing winds are basically northerly as seen in Figure 5-5. During the winter, it is extremely rare for winds to exceed 25 knots, but by the end of February, winds in excess of 25 knots occur 3 percent of the time. The winds in the north are westerly or northwesterly at 5-7 knots during the afternoon. In the evening, conditions are calm more than 60 percent of the time. In the south, winds are slightly stronger. During the evening, winds are northeasterly at 10 knots, and during the day they are southwesterly at 10-15 knots. With increased solar radiation, the winds become gradually stronger, with a greater frequency of a southwesterly direction with the approach of the hot season. Along the coast, a land/sea breeze sets up and affects the south as far as Bhuj. Bhuj winds are northeasterly at 5-10 knots in the morning, southwesterly 10 to 15 knots in the afternoon and early evening, and northeasterly at 5-10 knots by midnight.

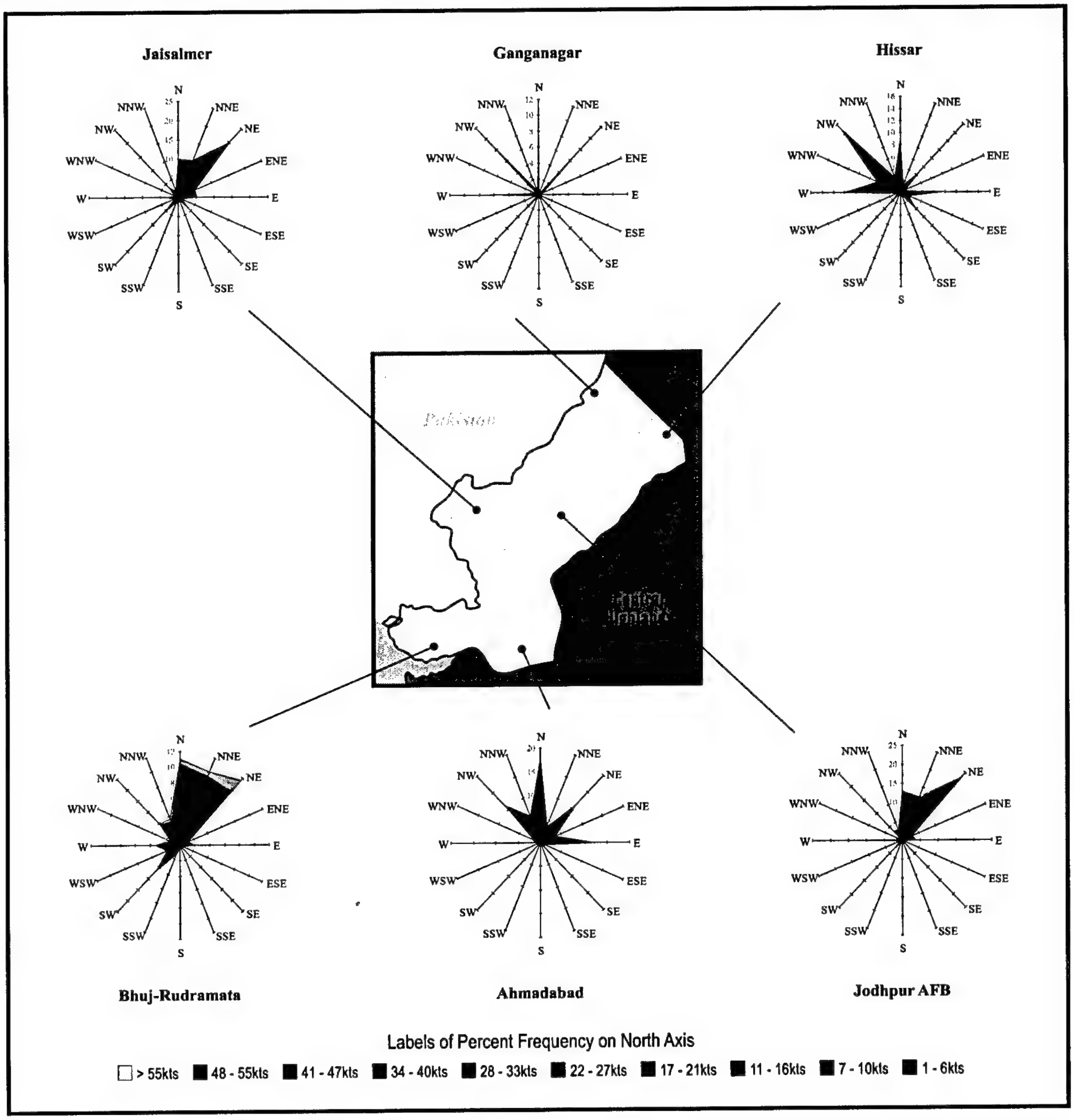


Figure 5-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The prevailing westerlies reach their maximum strength. Westerly flow prevails above 10,000 feet. Below 10,000 feet, winds are light and mostly from the west-northwest. Below 700 mb, westerly winds gradually strengthen from December to February. At 500 and 300 mb, westerlies dominate; 300-mb wind speeds average 60-90 knots at Ahmadabad. Farther north, December winds at 300 mb average 60-90 knots. By February, 300-mb winds increase to 120 knots. This reflects the southern periphery of the subtropical jet; the core is usually near 200 mb over the southern edge of the Himalayas. Figure 5-6 depicts January upper-level winds over Ahmadabad.

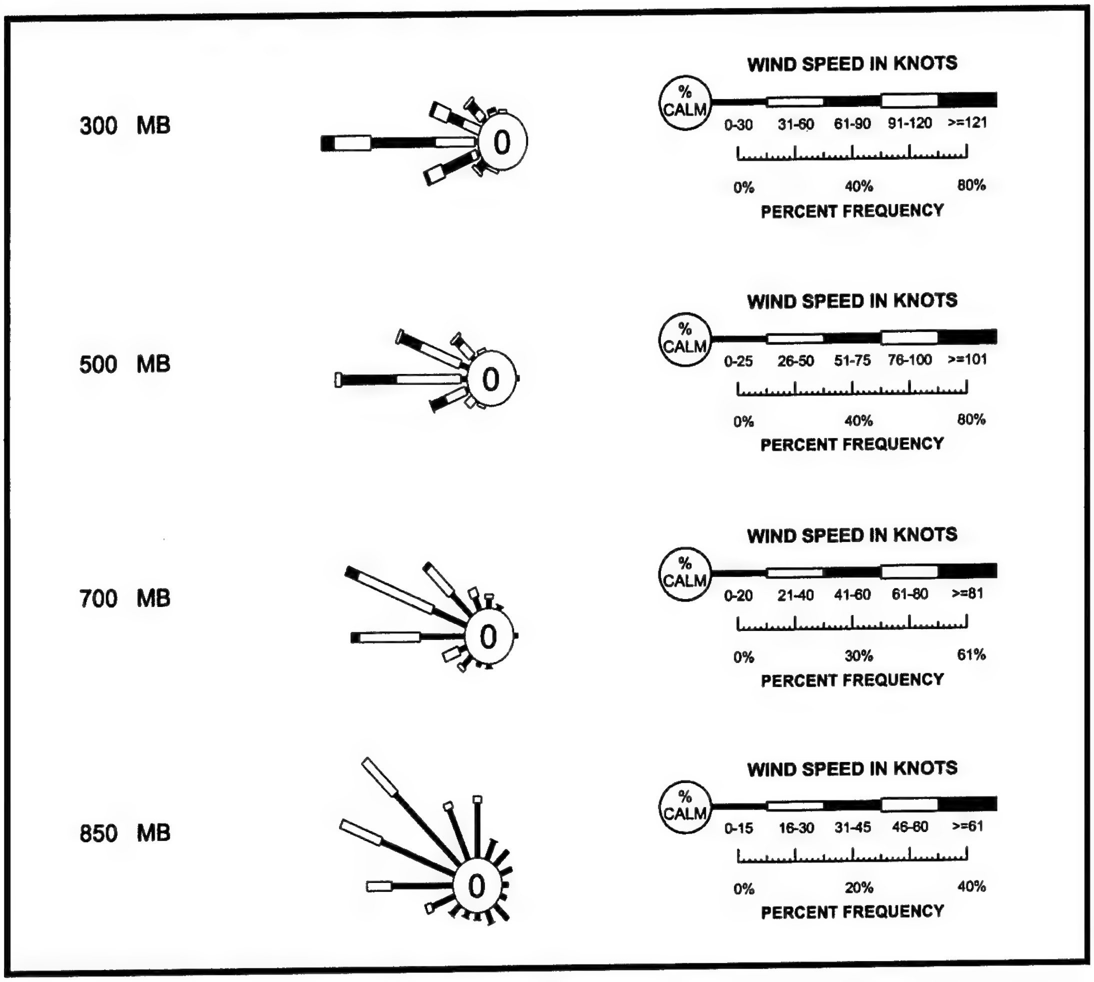


Figure 5-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Ahmadabad.

Precipitation. Terrain play a significant role in determining precipitation. The Hindu Kush and the Himalayas get most of the moisture associated with westerly disturbances. Precipitation is primarily due to the passage of shallow depressions from the west. The average is less than one inch (25 mm) of rainfall per month (see Figure 5-7). The average is less than 2 rain days per month; many places have less than one rain day all season. The extreme precipitation for any given month in the winter season is 2.5 inches (63 mm). The maximum 24-hour rainfall is less than 2 inches (51 cm). Thunderstorms are rare. One storm may occur at most stations all season, except Hissar, where 2-3 thunderstorms occur in February. Most thunderstorms do not produce hail. In the northwest, severe thunderstorms and hail storms are very infrequent, less than one every 3 years. Thunderstorms are primarily associated with westerly disturbances. Figure 5-8 shows the mean winter season precipitation and thunderstorm days.

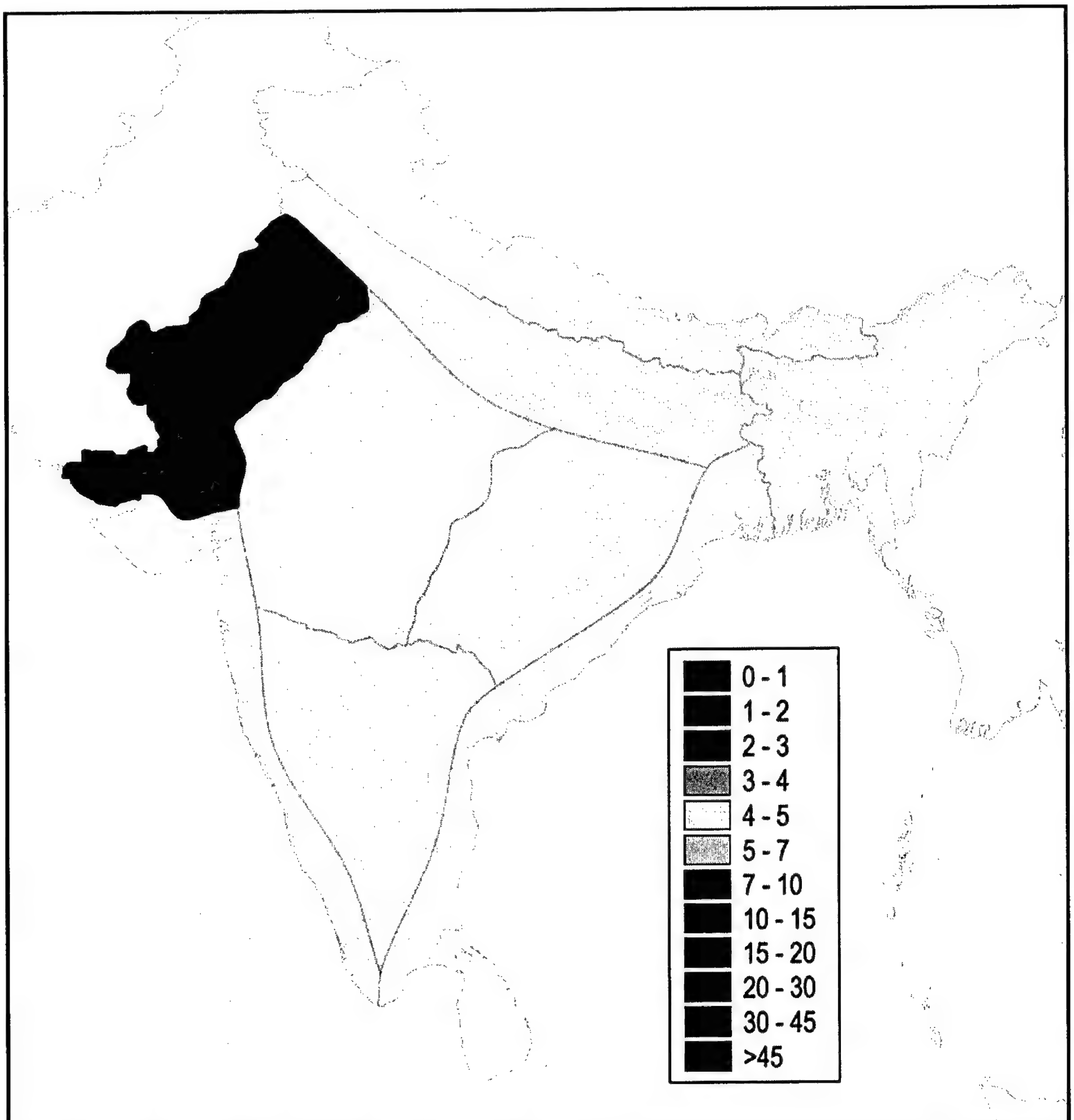


Figure 5-7. January Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

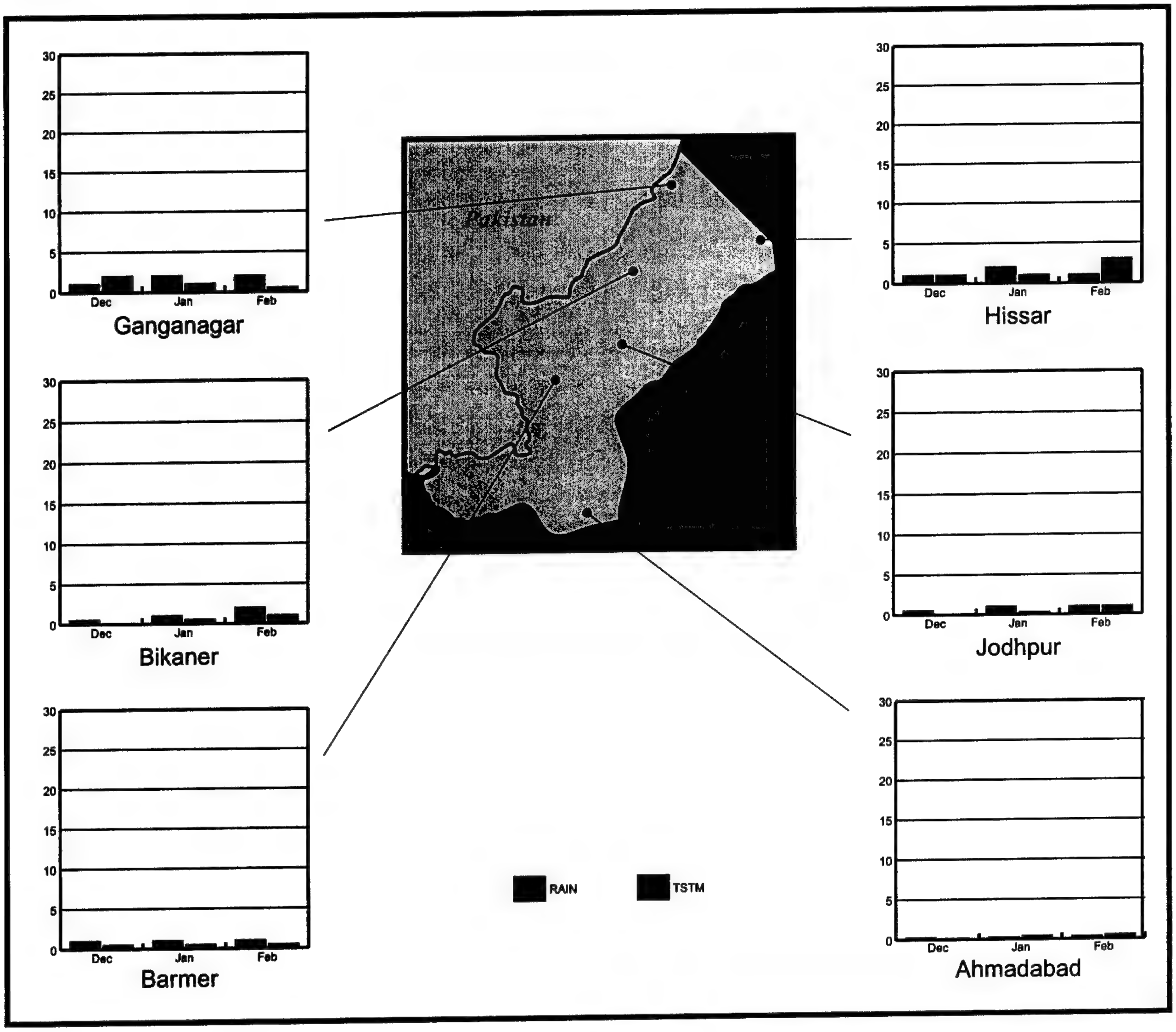


Figure 5-8. Winter Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures are mild. January is the coolest month at most stations. The winter mean daily range of temperatures is narrowest on the coast. The mean lows are 55° to 60°F (13° to 16°C) in the south and 40° to 45°F (4° to 7°C) in the north. The mean highs are 75° to 85°F (24° to 29°C) throughout the region except in the extreme north, where temperatures are 65° to 70°F (18° to 21°C). The extreme lows are below freezing at most locations. The lowest recorded temperature is 25°F (-4°C) at Hissar. The extreme highs exceed 100°F (38°C) in the south and 90°F (32°C) in the north. Ahmadabad had the highest recorded winter temperature, 103°F (39°C). The relative humidity averages 30-40 percent during the afternoon. In the morning the humidity increases to 55-65 percent. Figures 5-9 and 5-10 show the January mean maximum and minimum temperatures, respectively.

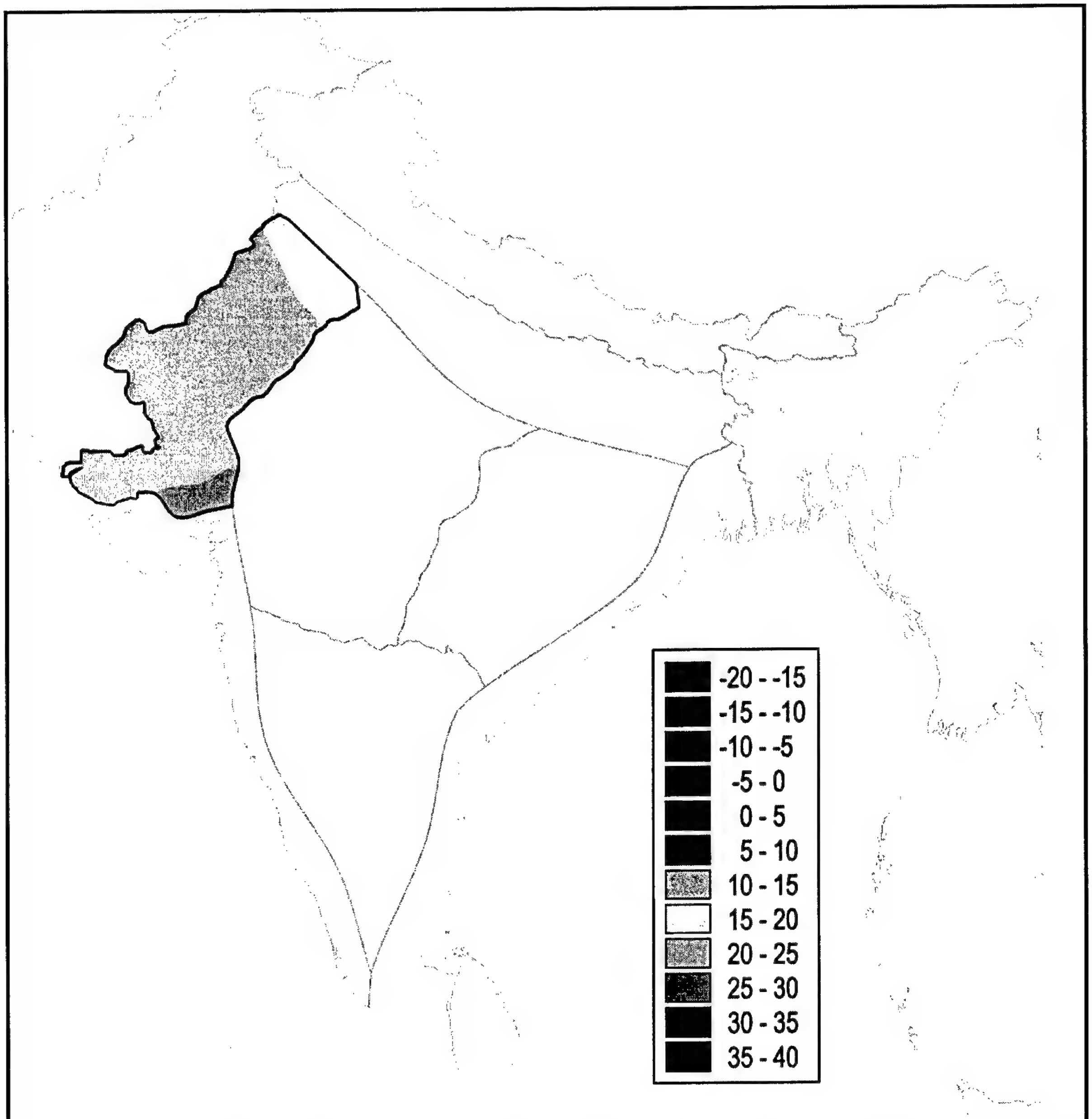


Figure 5-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

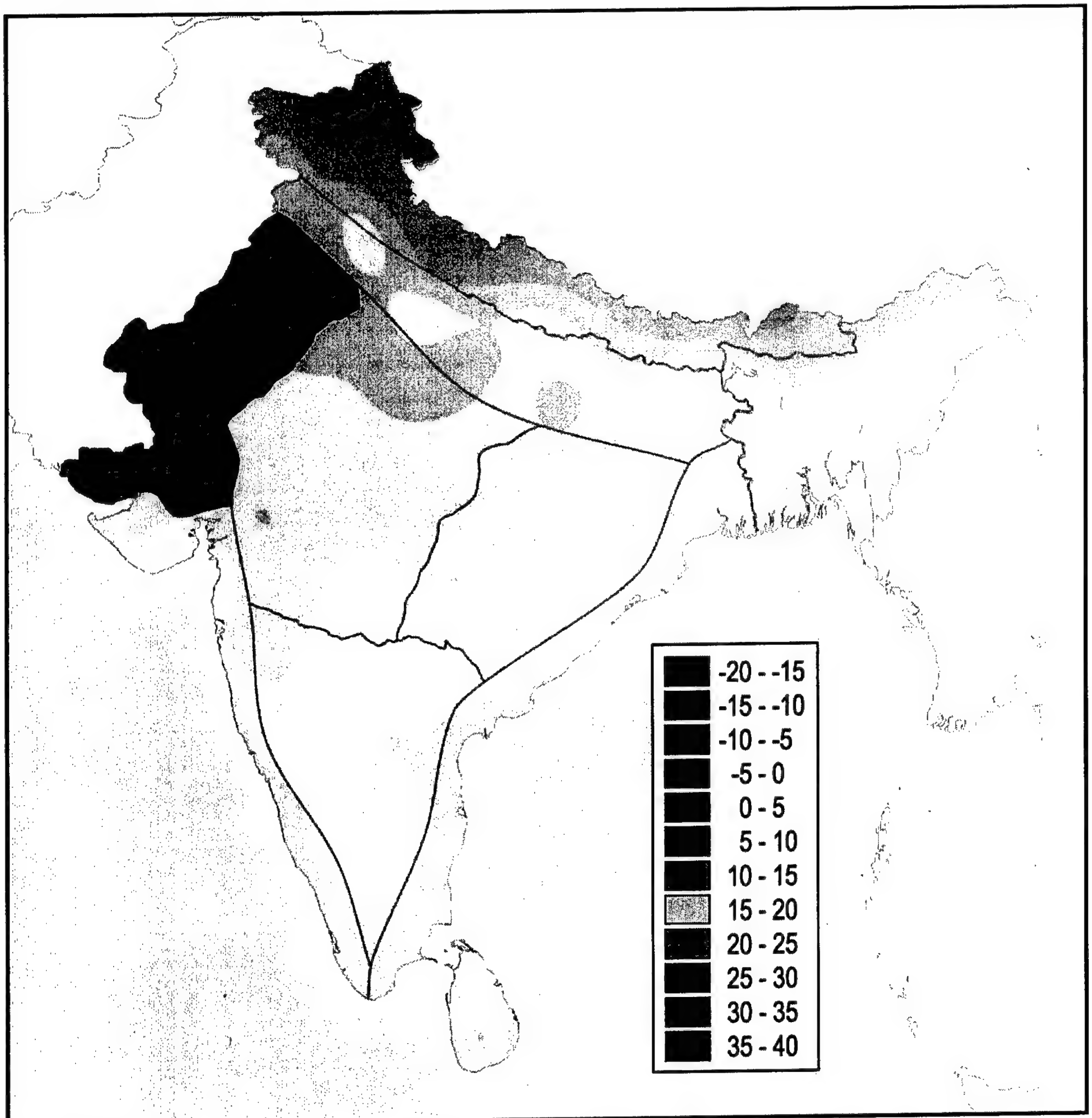


Figure 5-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often higher than the mean. Mean minimum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

Hot Season

General Weather. March begins the hot weather period. The western plains and hills are partly cloudy, extremely hot, and dry; temperatures rise all season. The "hot spot" shows a steady northward movement, so by May, the area of highest temperatures lies over the plains of northwestern India. The Asiatic high weakens and fades away in this season and it is gradually replaced by the Asiatic low. The STJ shifts north of the Himalayas and cuts off the path for westerly disturbances. The North Pacific and South Indian Ocean highs both shift north and west, and the Australian low dies to be replaced by the Australian high. Winds become light and variable. With these highs, the Asiatic low pulls the equatorial trough (ET) northward. By May, it is over south peninsular India and continues to move north. Southwesterly flow encroaches with the ET. The air that crosses the greater part of the northwest during the hot season is tropical continental with its source region in Southwest Asia. The warm, arid air is progressively heated as it travels over the deserts. Continental polar air still occasionally invades the area and causes a large drop in temperature, particularly at night. This occurs more in March than in April or May.

Tropical cyclones in the Arabian Sea or Bay of Bengal can send cloud cover over the region. Arabian Sea storms are not usually a threat but can recurve northeastward to make a rare landfall on the Rann of Kutch or in Pakistan. When they do this, rain and clouds reach far into the Thar Desert. Storms that make landfall in the northwest corner of the Bay of Bengal send extensive cloud cover and rain far to the west, but rarely bring more than high and middle cloud cover to the region. The same generally holds true for early monsoon depressions that may develop as early as May.

Sky Cover. Along the coast, stratus occurs during the early morning and evening hours and burns off in the heat of the day. This occurs in southwesterly, onshore flow from the east side of a weak trough that sets up just off the coast during the late hot season through the southwest monsoon. In the interior, afternoon cumulus develops in convective lifting but dissipates at sundown. When sufficient moisture is available, thunderstorms develop in the Aravalli Mountains. The occurrence of low ceilings decreases even more than compared to winter; it is higher in the afternoon than in the morning. Most of the low ceilings over the region have bases at 3,500-6,500 feet. Ceilings less than 5,000 feet rarely occur except in the Aravalli Range, where they occur 6-8 percent of the time. Ceilings less than 1,000 feet are extremely rare except on the windward slopes of the Aravallis, where they occur up to 6 percent of the time. Figure 5-11 shows occurrence rates of ceilings below 5,000 feet for selected locations.

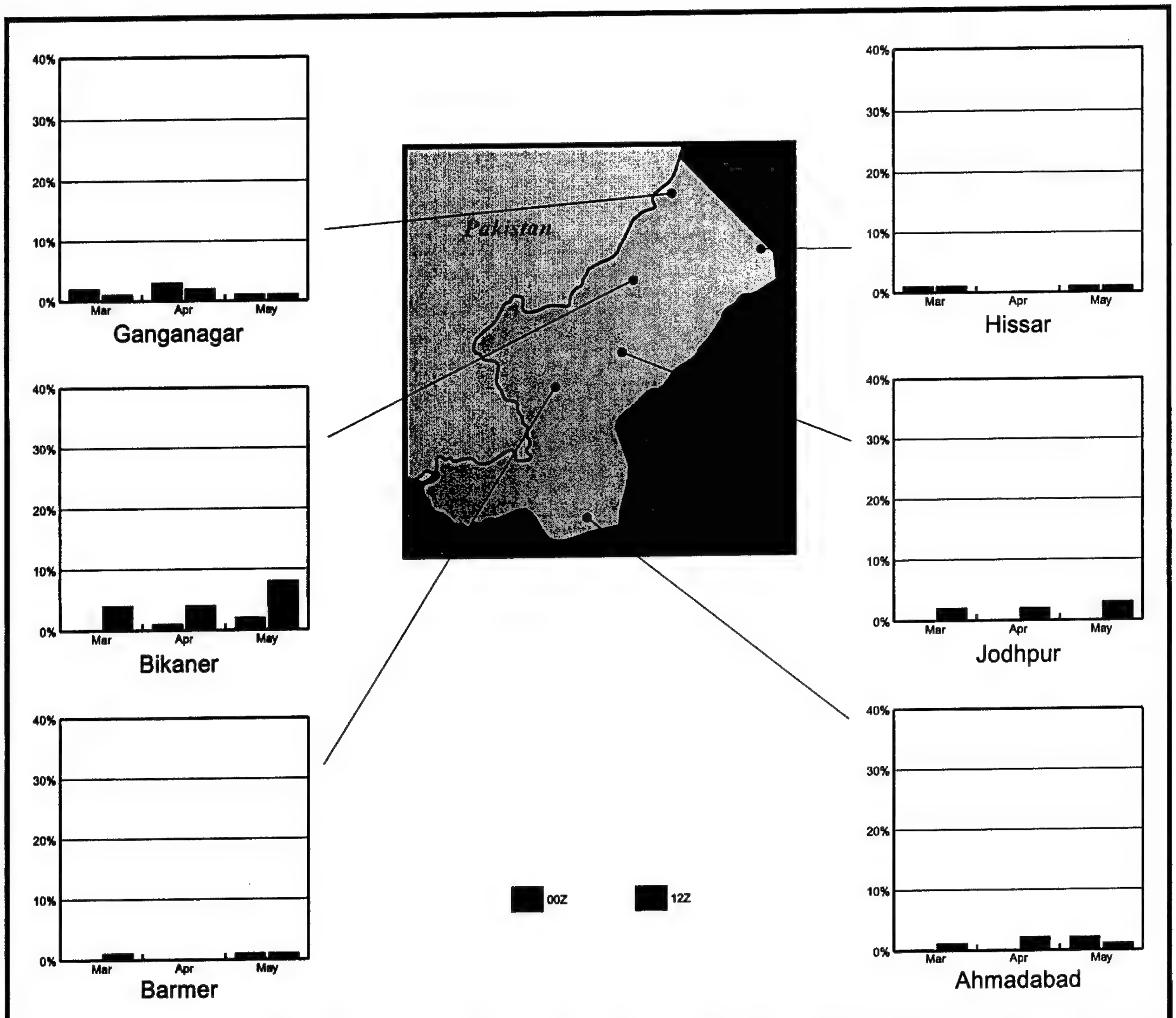


Figure 5-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. The occurrence of fog and precipitation in most areas increases slightly from March to May. Overall visibility in the region averages 4-6 miles (6,000-9,000 meters). The worst visibility occurs around sunrise and the best in the afternoon and evening. As noted in Figure 5-12, visibility differs from one area to another, mainly due to the location of the stations relative to water sources. Bikaner, in an area devoid of irrigation in the middle of the Thar Desert, has visibility less than 2 1/2 miles (4,000 meters) 4 percent of the time in March and up to 9 percent of the time in May. At the same time, Barmer, also in the Thar Desert but beside a canal, has visibility less 4,000 meters 9 percent of the time in March and 32 percent of the time in May. Visibility below 1/2 mile (800 meters) rarely occurs.

Hot season dust storms are common. During a dry thunderstorm dust squall, dust is often lifted hundreds of feet and becomes dense enough to reduce visibility. Dust storms are most common in the afternoons but may occur at any time. Dust raised by high winds often remains suspended in the air for a long time. Under intense dust storm conditions, dust will reduce visibility to less than 300 feet (less than 100 meters) for many hours. Dust storms are primarily associated with instability in the atmosphere, commonly with vigorous squalls in which winds often exceed gale force. An impending dust storm is usually preceded by a change in wind direction, a marked fall in temperature at the surface, and a rise in relative humidity. Thunderstorms are generally associated with these squalls, but lightning may not be visible through the thick dust or thunder heard over the noise of the wind. Dust storms occur 3-5 days a month in May throughout the entire region. One exception is Bhuj, on the Rann of Kutch, where dust storms rarely occur because of the higher relative humidity on the coast.

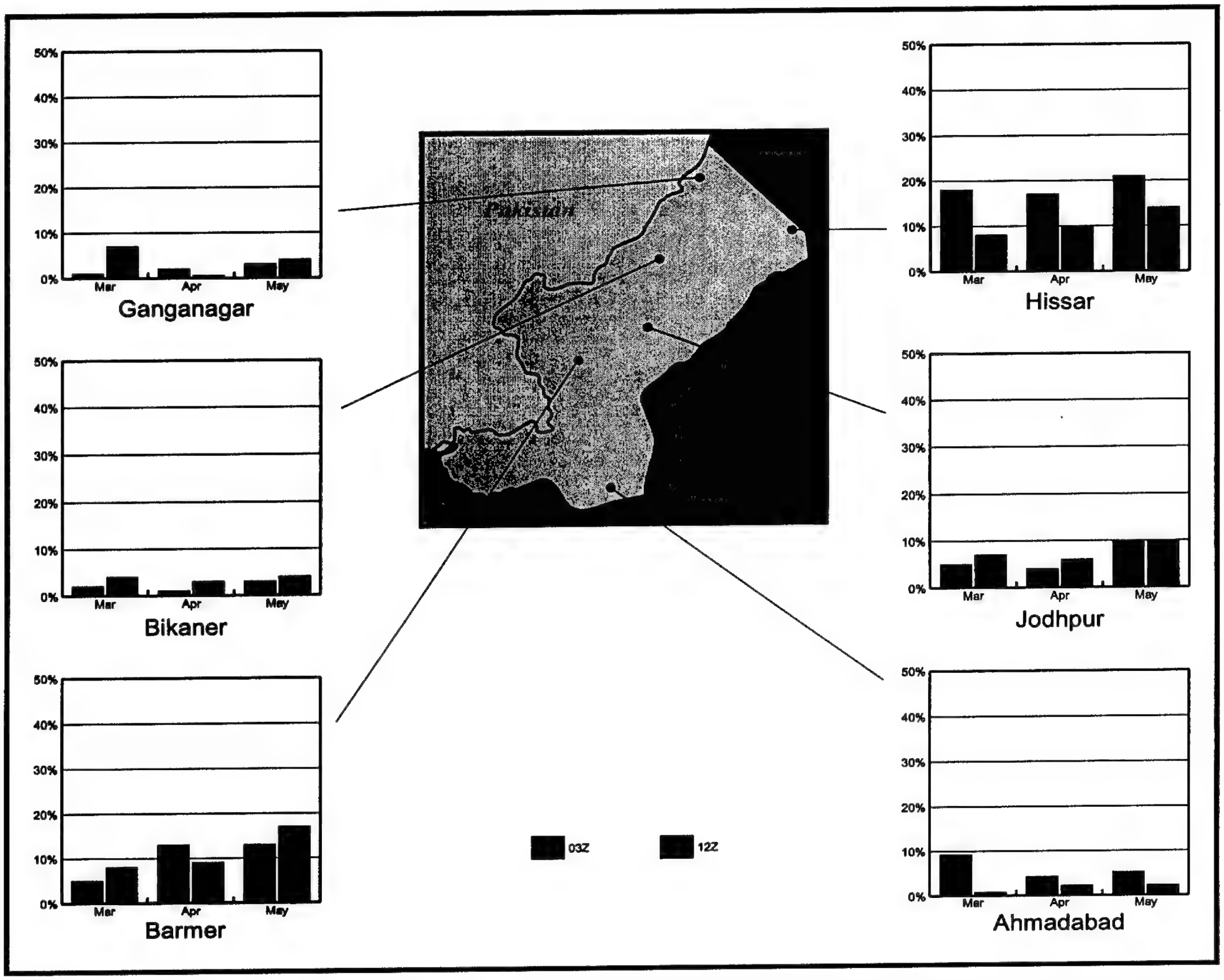


Figure 5-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The winds begin to transition from northerly to southerly flow. The southwest monsoon flow becomes evident by May. Early in the season, in evening through morning hours, conditions are primarily calm. When not calm, a westerly through northwesterly, 5-7 knots winds prevail as shown on the wind roses for selected locations in Figure 5-13. Through the afternoon, surface winds are 5-7 knots with infrequent southwesterly winds at 10-15 knots. By May, the winds are from the southwest at 5-7 knots at all hours, and winds greater than 15 knots increase to 25 percent of the time in most areas. Bhuj, on the coast, experiences southwesterly flow of greater strength; the average winds during the afternoon are greater than 10 knots more than 30 percent of the time. The night land breeze is overridden by the predominant southwesterlies by May and only returns under weak large-scale flow during monsoon breaks.

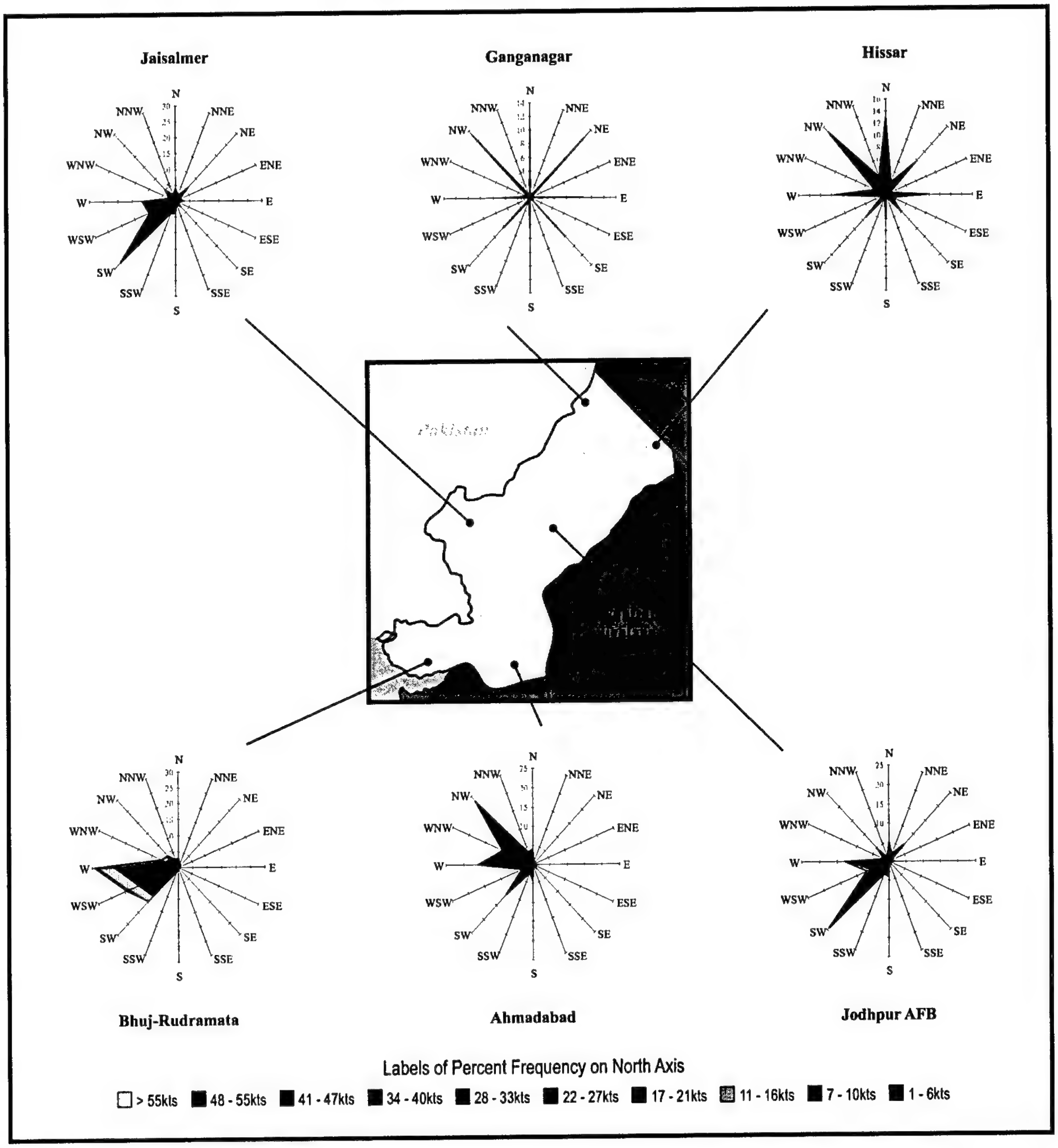


Figure 5-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The northwest region remains under westerly winds. At 700 mb, winds are westerly at speeds near 15 knots. The 300 mb winds are 30-60 knots; occasionally, 90 knots will occur. The subtropical jet begins to move north near the end of the season, but the southern periphery of the jet brings west winds at speeds of up to 100 knots over northern India. Figure 5-14, a composite, shows the upper-air winds typically found at Ahmadabad and Jodhpur in April.

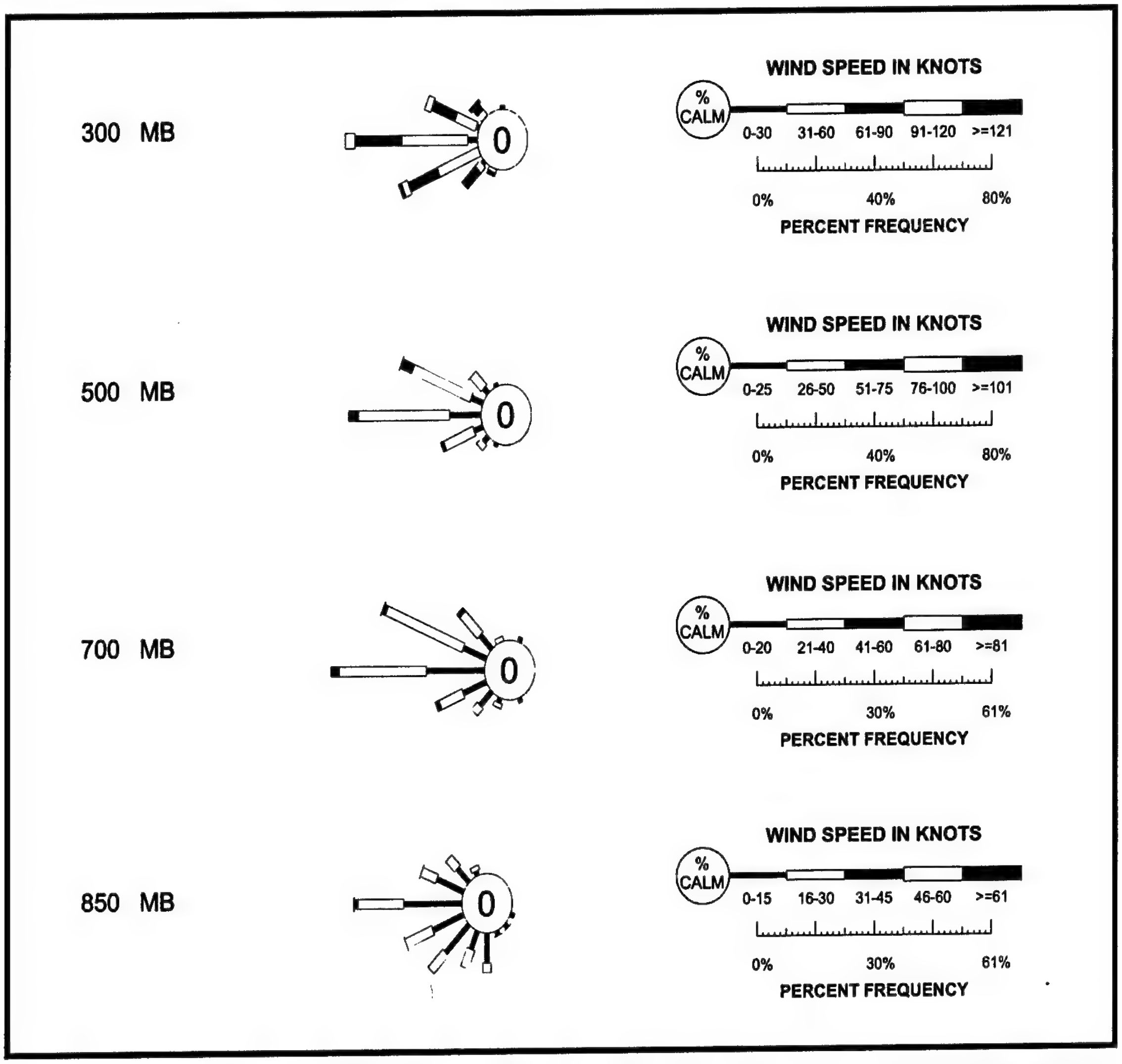


Figure 5-14. April Upper-Air Wind Roses. The composite wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb at Ahmadabad and Jodhpur.

Precipitation. Rainfall occurs chiefly with thunderstorms, and is very irregularly distributed. The average is less than an inch (25 mm) of rain per month. Rain occurs less than two days per month for the entire region; most stations have less than one rain day all season. The greatest amount of rain for March is 2 inches (51 mm); the amount rises to less than 5 inches (127 mm) in May throughout most of the region as the southwest monsoon approaches. Along the coast, the greatest amount of precipitation in May increases up to 8.7 inches (221 mm). The maximum 24-hour rainfall is 3-4 inches (76-102 mm) throughout most of the region except for Bhuj. There, a rare tropical storm brought a May 24-hour maximum precipitation of 7 inches (178 mm). Figure 5-15 illustrates the April mean precipitation amounts.

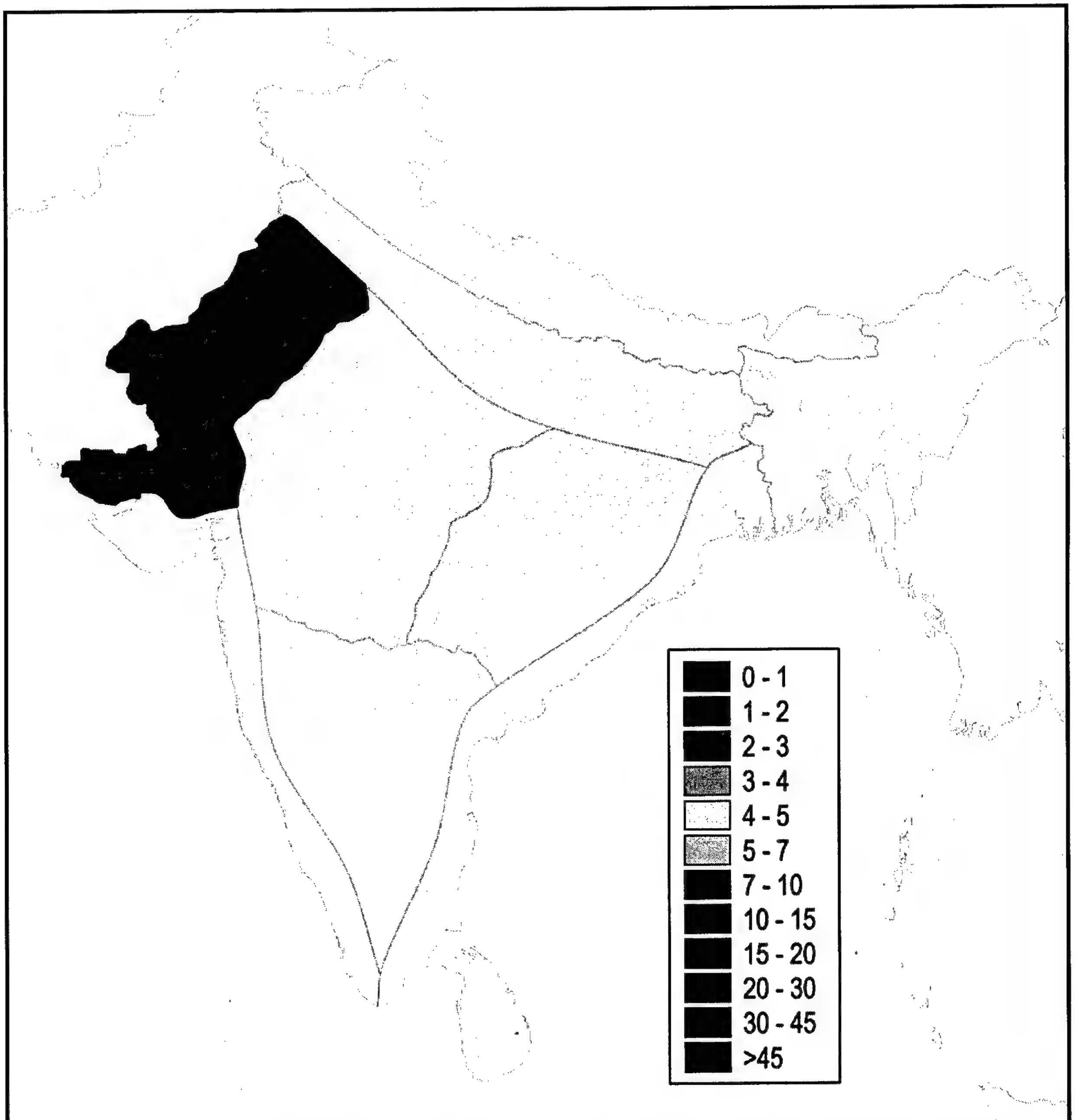


Figure 5-15. April Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

Thunderstorms are infrequent, and most occur with convective heating of the air mass. Most stations average one thunderstorm per month, except for Jodhpur, which experiences 6 thunderstorms in May. Figure 5-16 shows seasonal precipitation and thunderstorm days. .Jodhpur gets them because they are at the southwestern foot of a higher plateau, at the point of a progressively narrower plain, and orographic lifting of the southwesterly flow in May carries moist air to the area. Severe thunderstorms rarely occur; hail occurs less than once every 3 years. Tornadoes, a by-product of severe thunderstorms, infrequently occur. Of all tornadoes that affect India, less than 5 percent occur in northwest India. Most tornadoes in this region are associated with strong western disturbances.

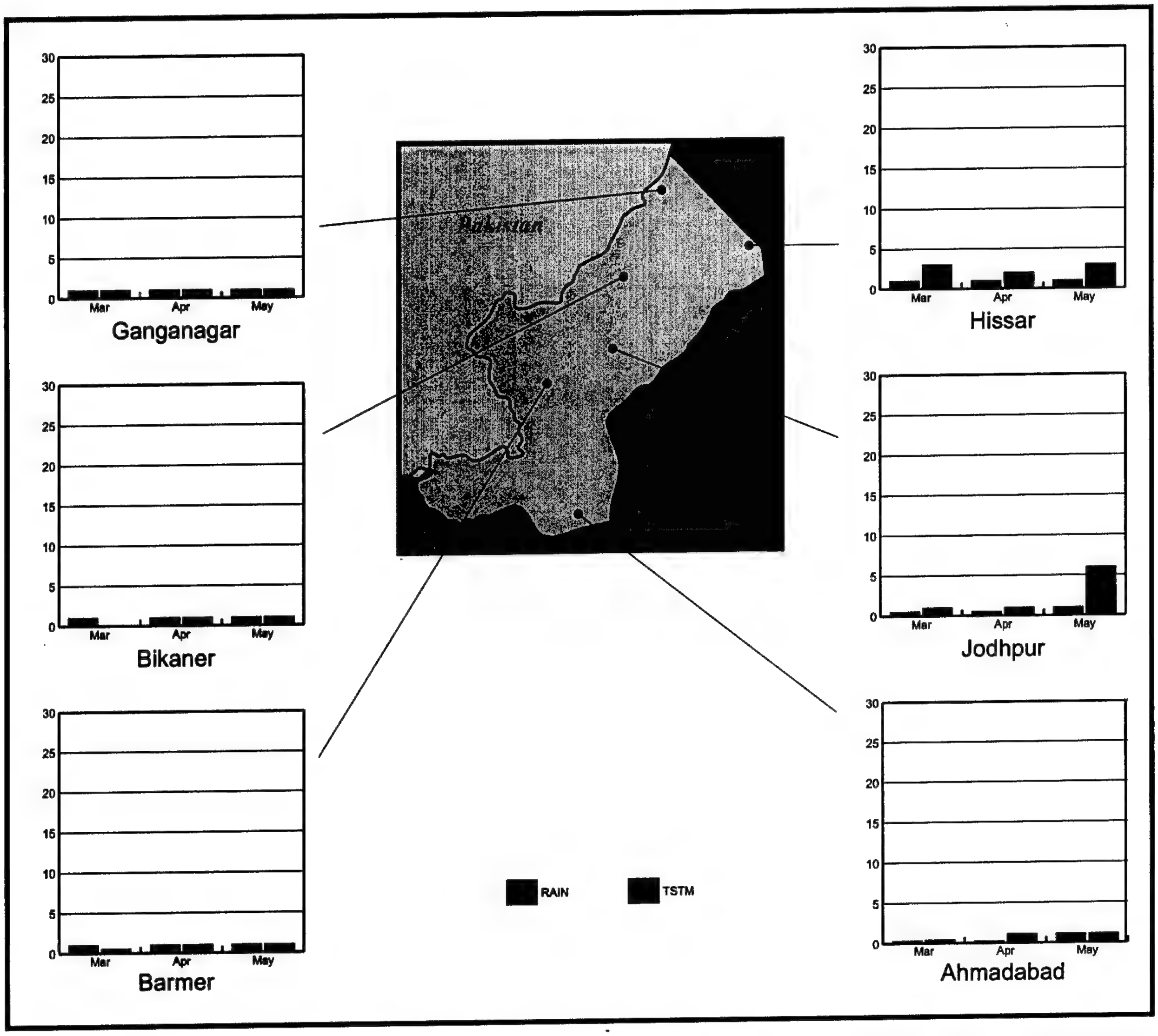


Figure 5-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. There is a steady northward movement of the area of greatest heat. By May, the center of highest temperatures lies over the northern reaches of the region, where temperatures greater than 120°F (49°C) are common. Sand storms sharply reduce the temperature, and when accompanied by sudden rainfalls, short-term relief from the heat occurs. The mean lows in March are 60° to 65°F (16° to 18°C) in March and rise to 75° to 80°F (24° to 27°C) in May. The mean highs are 85° to 90°F (29° to 32°C) in March and increase to 100° to 105°F (38° to 41°C) in May. The March extreme low recorded is 34°F (1°C) at Bikaner, and the extreme high recorded, also at Bikaner, is 121°F (50°C) in May. For most of the region, the mean diurnal temperature range is 30 Fahrenheit (17 Celsius) degrees, but along the coast, the mean daily range is much lower because of the higher moisture content of the air. The average relative humidity during the afternoon is 20-25 percent, while in the morning the humidity averages 65-75 percent. The relative humidity sometimes drops to one percent in the Thar Desert. Figures 5-17 and 5-18 show the April mean maximum and minimum temperatures, respectively.

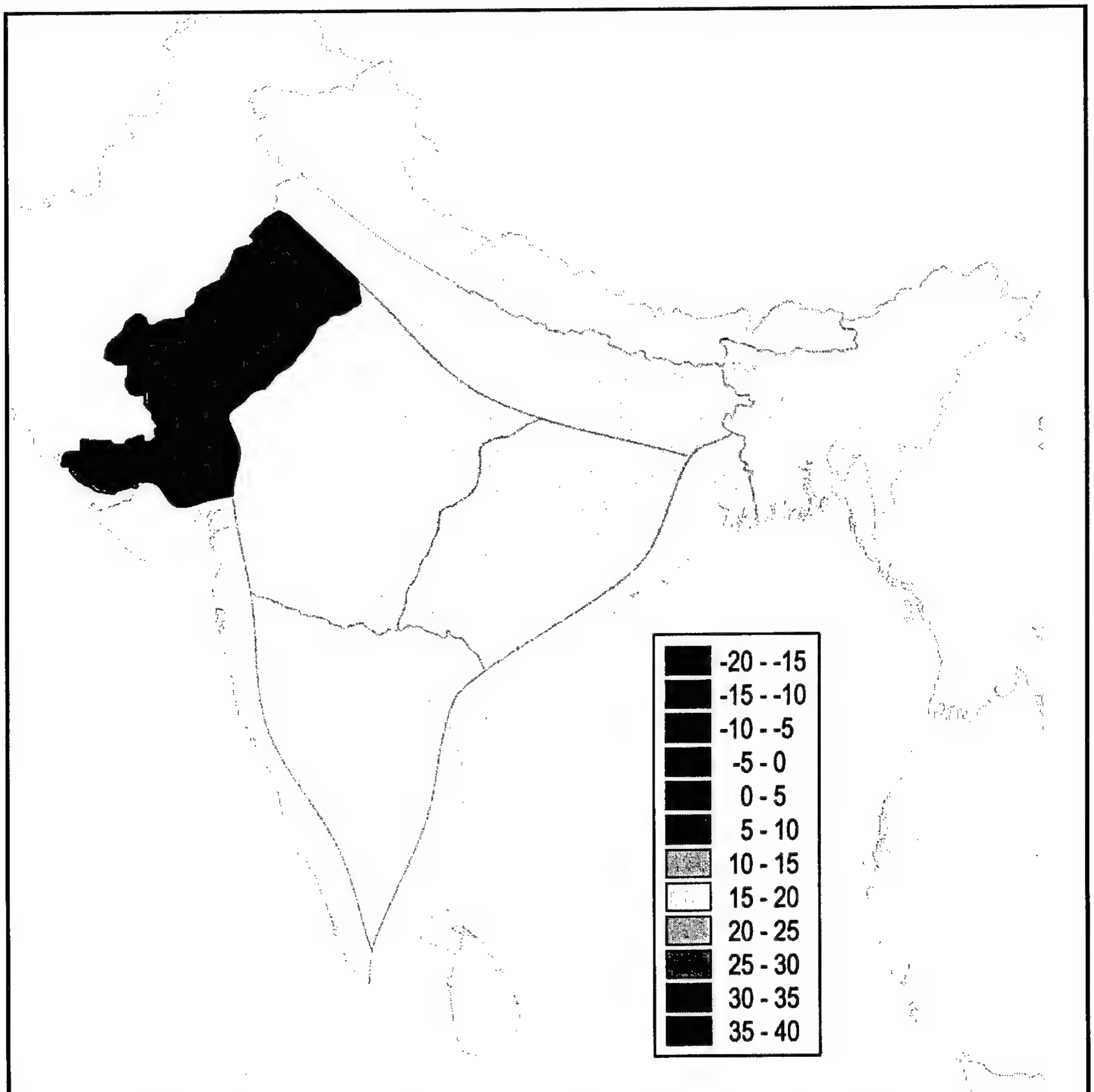


Figure 5-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

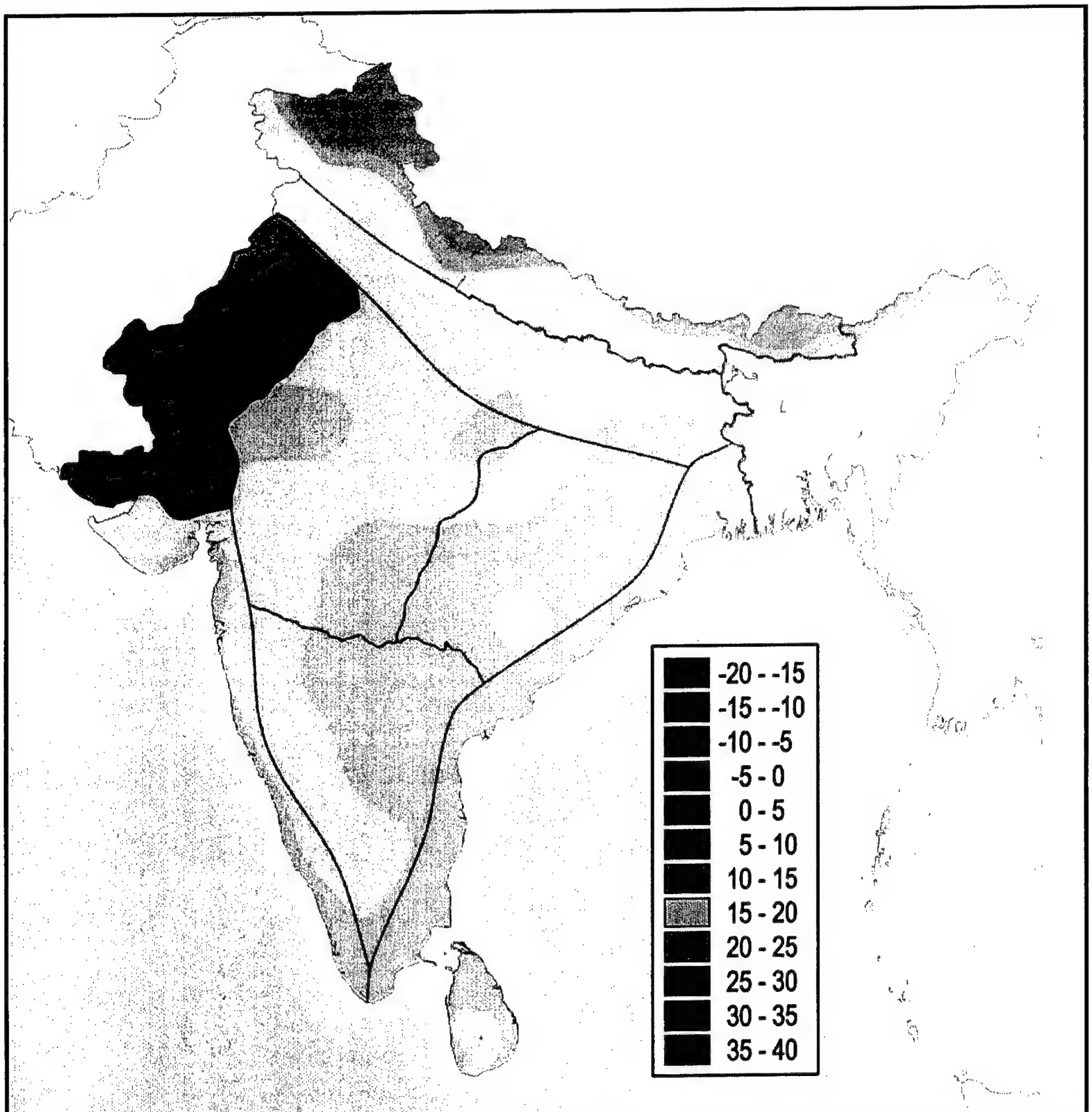


Figure 5-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. By the end of May, a pressure gradient is established between the Asiatic low and the semipermanent, oceanic highs. The thermal high over Australia helps push the equatorial trough (ET) northward even as the Asiatic low pulls it. The ET shifts north and brings the southwest monsoon flow with it. The southeast trades of the Southern Hemisphere cross the equator and become southwest winds as they are deflected in the Northern Hemisphere. The southwest monsoon has 2 branches: the Arabian Sea branch, which crosses the Western Ghats in peninsular India as a west-to-southwest winds, and the Bay of Bengal branch. The southwest monsoon current normally advances into Bangladesh and the tip of the peninsula by late May and moves north and west from there. By the first of July, southwest flow is usually established over the Thar Desert. The Thar is under the northern periphery of the southwest monsoon and the rains are hardly felt there.

In this season, the TEJ and the Somali jet are both present. The Somali jet funnels Southern Hemisphere moisture across the Arabian Sea into India. The TEJ provides an outflow mechanism for disturbances of all types in both the Arabian Sea and the Bay of Bengal. These disturbances, such as monsoon depressions and tropical cyclones, do not generally affect the region directly, but they can spread rain and cloud cover far into the interior from both directions. On very rare occasions, a tropical cyclone in the Arabian Sea recurves to the northeast instead of to the northwest and makes landfall on the Rann of Kutch or in Pakistan. Either way, rain and heavy cloud cover spreads over the region with these storms.

Sky Cover. The cloud amounts in this season are greatest on the coast and over or near the Aravalli Range. Low cloudiness peaks in July and August. On the coast, morning ceilings below 5,000 feet occur 15-20 percent of the time in June, August, and September and peak at 25-35 percent of the time in July. Ceilings peak at noon with a maximum occurrence of 45-55 percent of the time in July and 35-45 percent of the time in June, August, and September. By late afternoon and through the night, they occur 10-20 percent of the time all season. Inland, the occurrence rates are much lower, only 5-10 percent of the time in the mornings and rarely the rest of the day. On higher terrain and in the north, cloud cover develops in orographic lift and ceilings below 5,000 feet occur in windward areas 15-20 percent of the time most of the day and 30-35 percent of the time in the afternoons. Jodhpur is a classic example. At the top of a funnel-shaped plain and at the foot of higher terrain in the Aravalli foothills, Jodhpur gets ceilings below 5,000 feet 37 percent of the time in July and August under lifted southwest monsoon flow most of the day and 40-45 percent of the time in the afternoons. In sites not associated with higher ground, occurrence rates are below 5 percent of the time all season and all day, as seen in Figure 5-19. Ceilings below 1,000 feet occur rarely in most of the region. Only those places under windward flow and around higher terrain get them 15-20 percent of the time in the mornings and under 5 percent of the time the rest of the day.

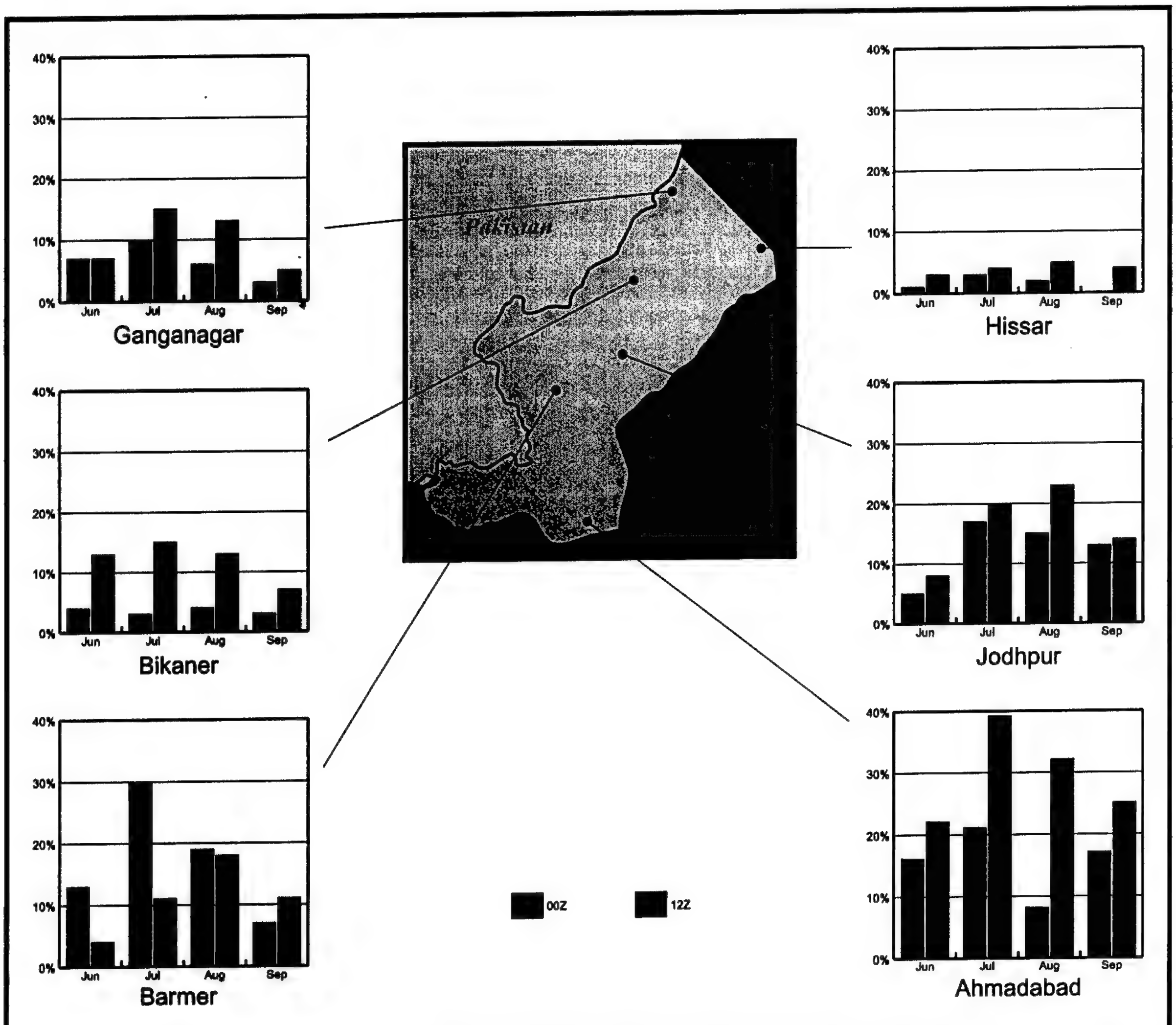


Figure 5-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is restricted by smoke and dust haze near major populated areas where there is no steady wind flow. This is most noticeable near large towns or cities where temperature inversions and industrial pollution are the primary causes. Visibility is better along the coast; even though the afternoon sea breeze brings in salt haze, sustained wind flow keeps visibility high. Visibility in rain is 3-5 miles (4,800-8,000 meters) but can go as low as 1/2 mile (800 meters). Fog occurs during and after rain. Early morning ground fog can occur in the Rann of Kutch in early morning hours.

In the northwest, the prime restrictions to visibility are dust and haze. As reflected in Figure 5-20, visibility at most places is poorest during the late morning through afternoon. Radiation inversions break by late morning and winds kick up dust to produce lower visibility. Hissar, for example, experiences visibility less than 4,000 meters at 0800L greater than 40 percent of the time in June in dust and haze. The overall occurrence of visibility less than 4,000 meters in the region holds a wide range of values. Sri Ganganagar, Bhuj, Bikaner, and Ahmadabad experience visibility less than 4,000 meters less than 10 percent of the time. In Barmer, and Jodhpur, poor visibility peaks out in June with occurrences of less than 4,000 meters 20-45 percent of the time. Visibility less than 1 1/4 miles (2,000 meters) occurs rarely in most places. Places like Hissar and Khandar have it 15 percent of the time in June in dust but only 5-8 percent of the time the rest of the season. Dust storms continue to occur fairly frequently, especially with dry convection. Dust storms usually occur 5-9 days per months in the Thar Desert and 1-3 days per month everywhere else except for the coast, where relative humidity is high enough to keep down the dust.

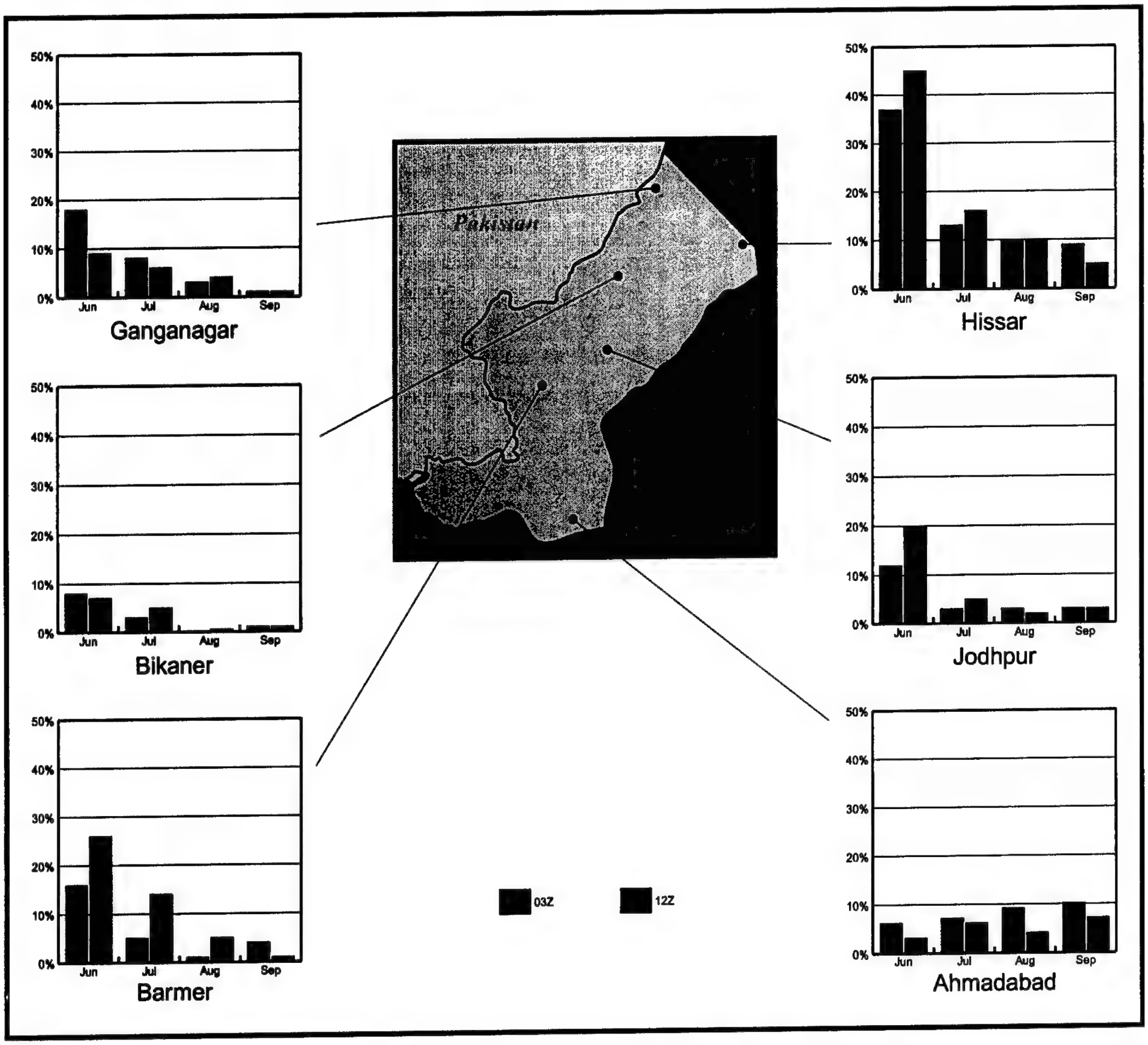


Figure 5-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The surface winds in the north are primarily variable at 5 to 7 knot in June then become southeasterly-southwesterly at 5-7 knots in July and August, as seen in Figure 5-21. The interior has southwesterly winds at 8-12 knots; night winds are lighter, 5-10 knots. Along the coast, daytime winds are sea breeze enhanced. Winds at Bhuj are southwesterly 12-18 knots with winds occasionally greater than 25 knots. At Dohad, the winds are southwesterly at 10-15 knots all season. The winds are greater than 20 knots 20 percent of the time and greater than 30 knots less than 5 percent of the time. Dohad, in a valley between two northeast-southwest ridges, has stronger channel winds.

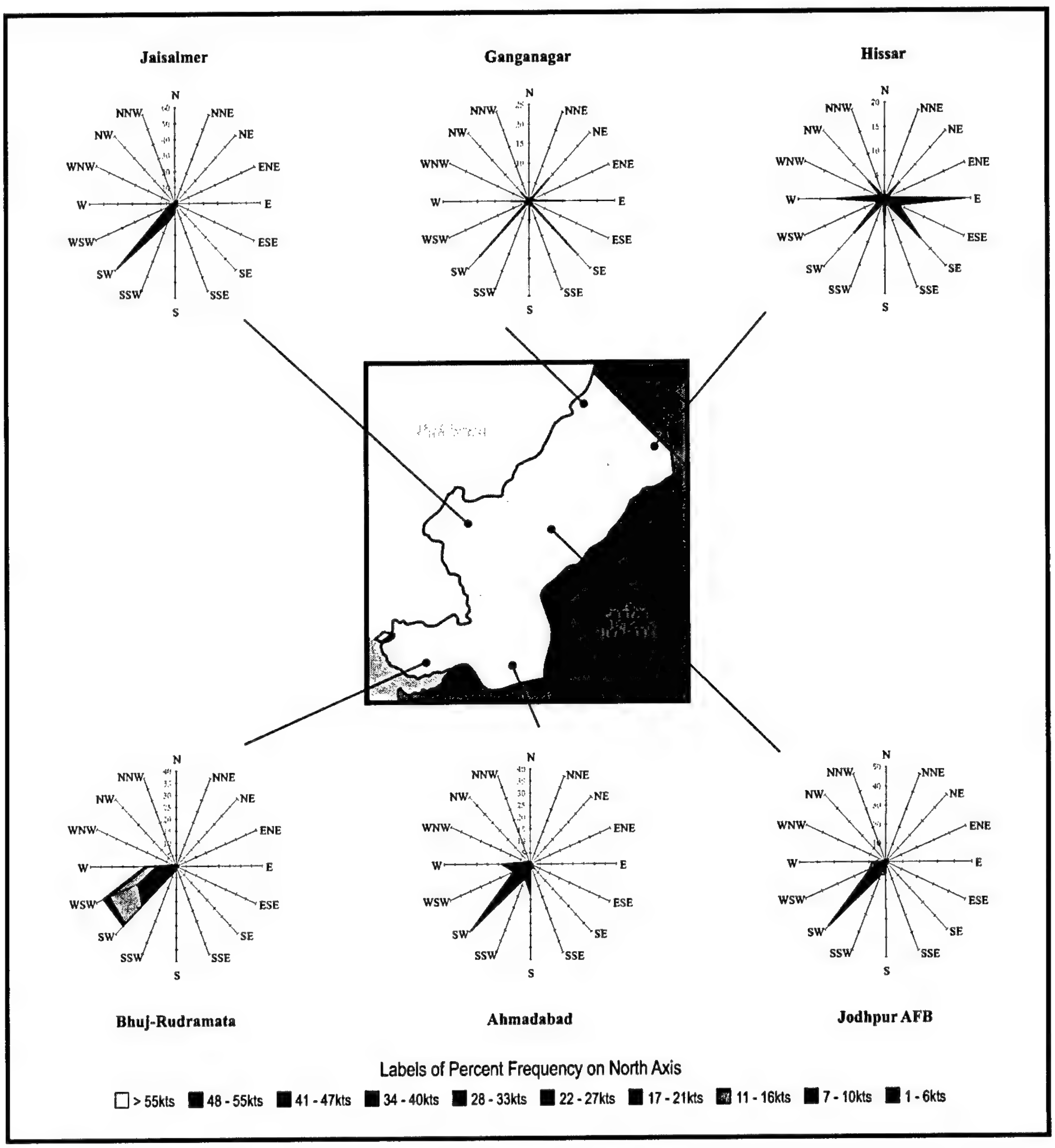


Figure 5-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. Two upper-air wind systems exist in South Asia: the monsoon westerlies and the tropical easterlies. The monsoon westerlies reach 700 mb. Winds in the monsoon westerlies are generally 25 to 50 knots. Tropical easterlies prevail to 300 mb with speeds generally near 30 knots but reaching 60 knots at higher levels. Figure 5-22 is a composite showing the upper-air winds typically found over Ahmadabad and Jodhpur in July.

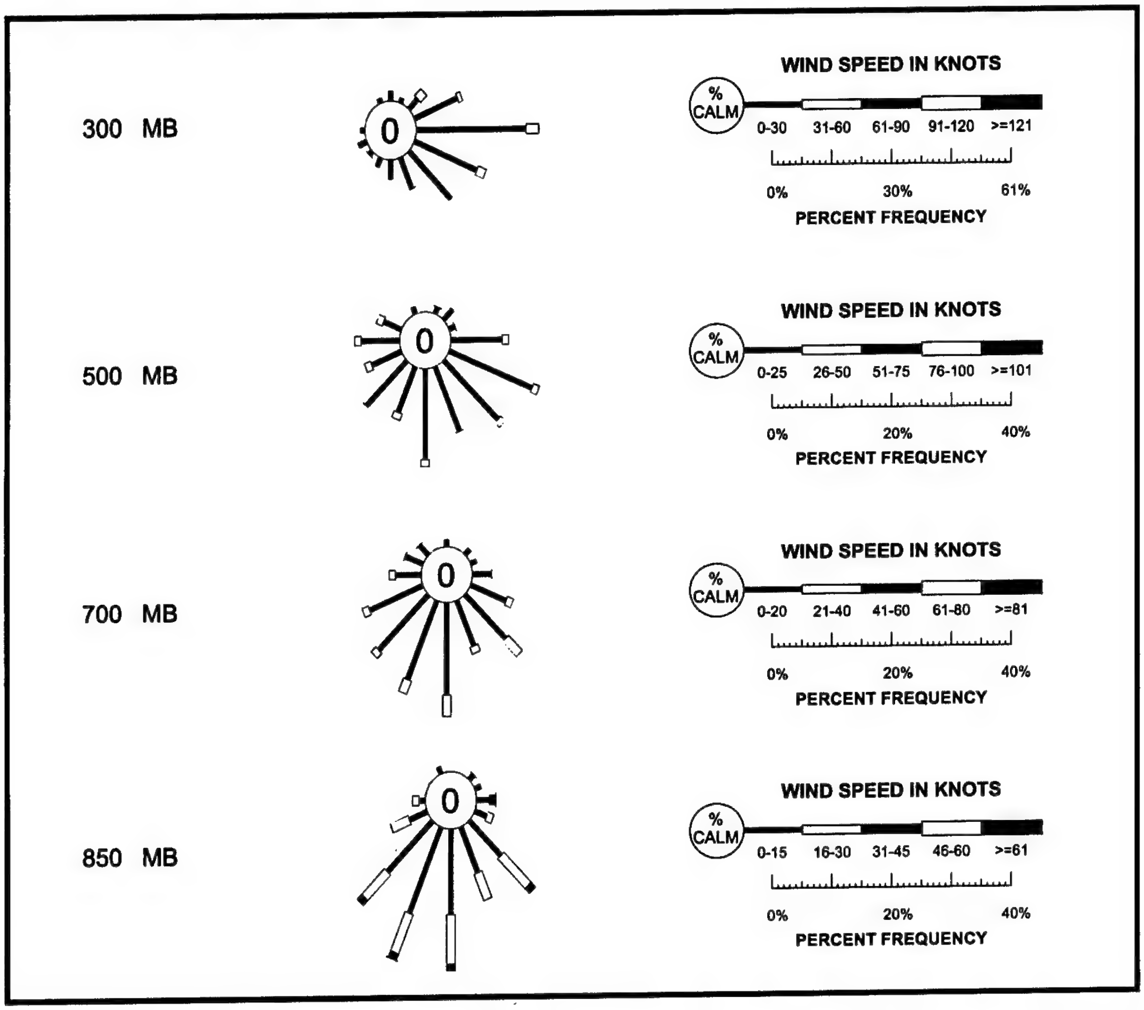


Figure 5-22. July Upper-Air Wind Roses. The composite wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb over Ahmadabad and Jodhpur.

Precipitation. The southwest monsoon accounts for over 90 percent of the annual rainfall. The rainfall distribution varies widely from year to year. On average, rain can be expected over a period of 3 weeks during the southwest monsoon. Days with precipitation generally average less than 10 per year. Although infrequent, exceedingly heavy rains that last 1-2 days in a localized area, can cause severe floods. This occurs when an upper-tropospheric easterly and westerly trough come close to one another and develop an upper-level "anticyclonic shear zone" between them. Between the two 850-mb lows (associated with the upper-level troughs), a line of convergence sets up beneath the upper-level shear zone and induces heavy precipitation. Figure 5-23 shows the mean rainfall amounts for July.

The average is 1-2 inches (25-52 mm) in June, except for Ahmadabad, where rain averages 3 inches (76 mm). In the south, the highest average rainfall occurs in July; Ahmadabad averages 12 inches (305 mm), and Bhuj averages 6 inches (152 mm). North of this area, the highest average rain fall amounts do not occur until August, 4-6 inches (102-152 mm). Ahmadabad continues to experience a substantial amount of precipitation in September with an average of 6 inches (152 mm).

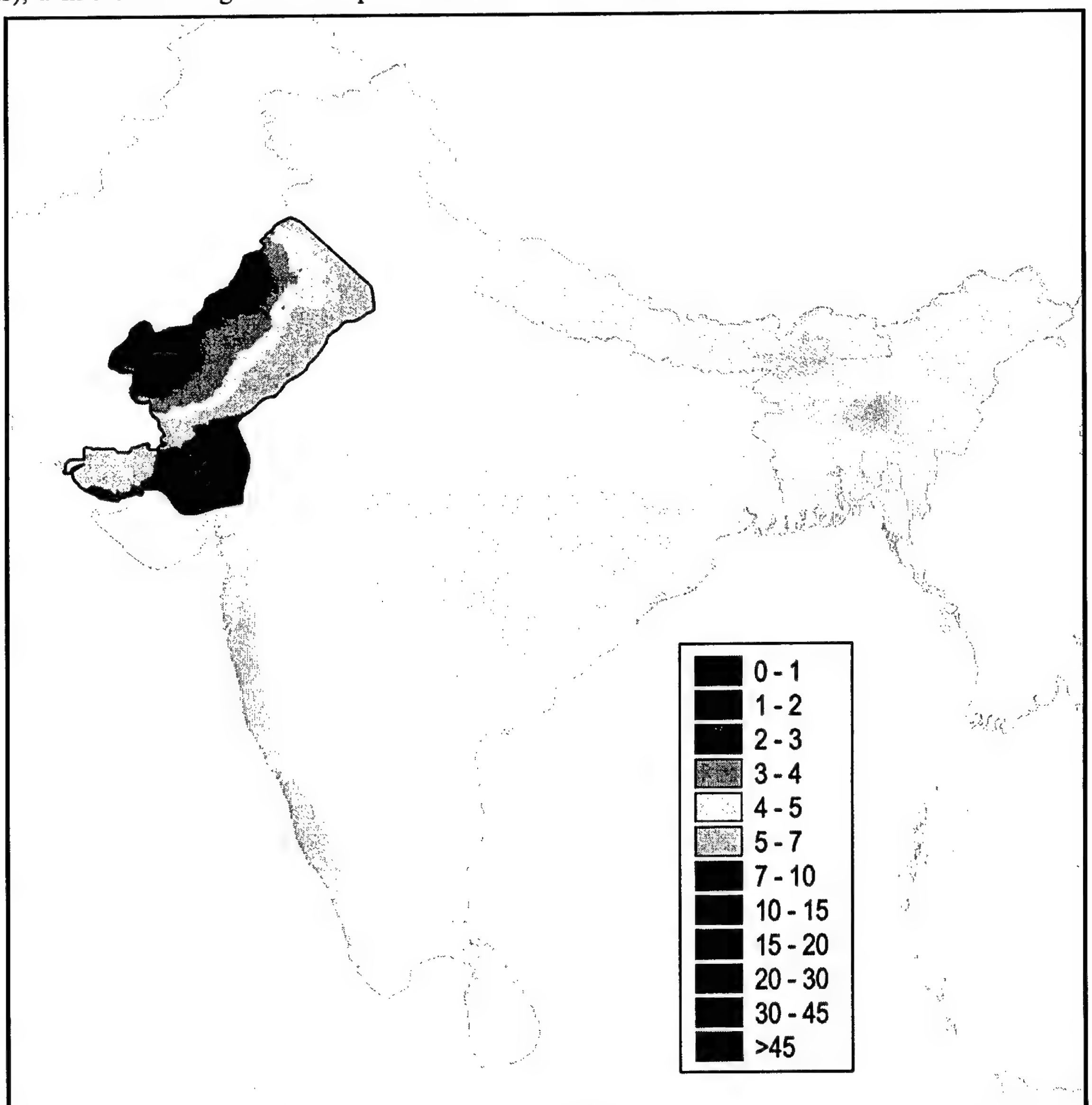


Figure 5-23. July Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

There are 3-5 rain days in June and 5-7 in July through September. Ahmadabad, at the foot of the Aravalli Range, experiences 13 and 11 days of rain in July and August, respectively (see Figure 5-24). The record amount of rain for the season is 3-6 inches (76-152 mm) a month in the Thar Desert and 25-30 inches (635-762 mm) along the southern Aravalli range and Rann of Kutch. Deesa, at the foot of the Aravalli Range, once had 14 inches (356 mm) of rain in August. Maximum 24-hour precipitation is 5-7 inches (127-178 mm) at most places. During the southwest monsoon, the number of days with thunderstorms only increases significantly along the Aravalli Range, where they occur 6-8 days in some places. Elsewhere, thunderstorms occur 1-2 days per month. Mesoscale Convective Complexes (MCCs) affect the region 2-3 times in August and September with the retreat of the southwest monsoon. Hailstorms are very rare; one every 3-4 years is normal.

Drought is a frequent occurrence. Every 2-3 years, northwest India experiences a large deviation from normal in rainfall amounts. Droughts that last 4-5 years are not uncommon; there have been instances of droughts that lasted 9-10 years around Jaisalmer. Severe droughts accompany prolonged breaks in the southwest monsoon.

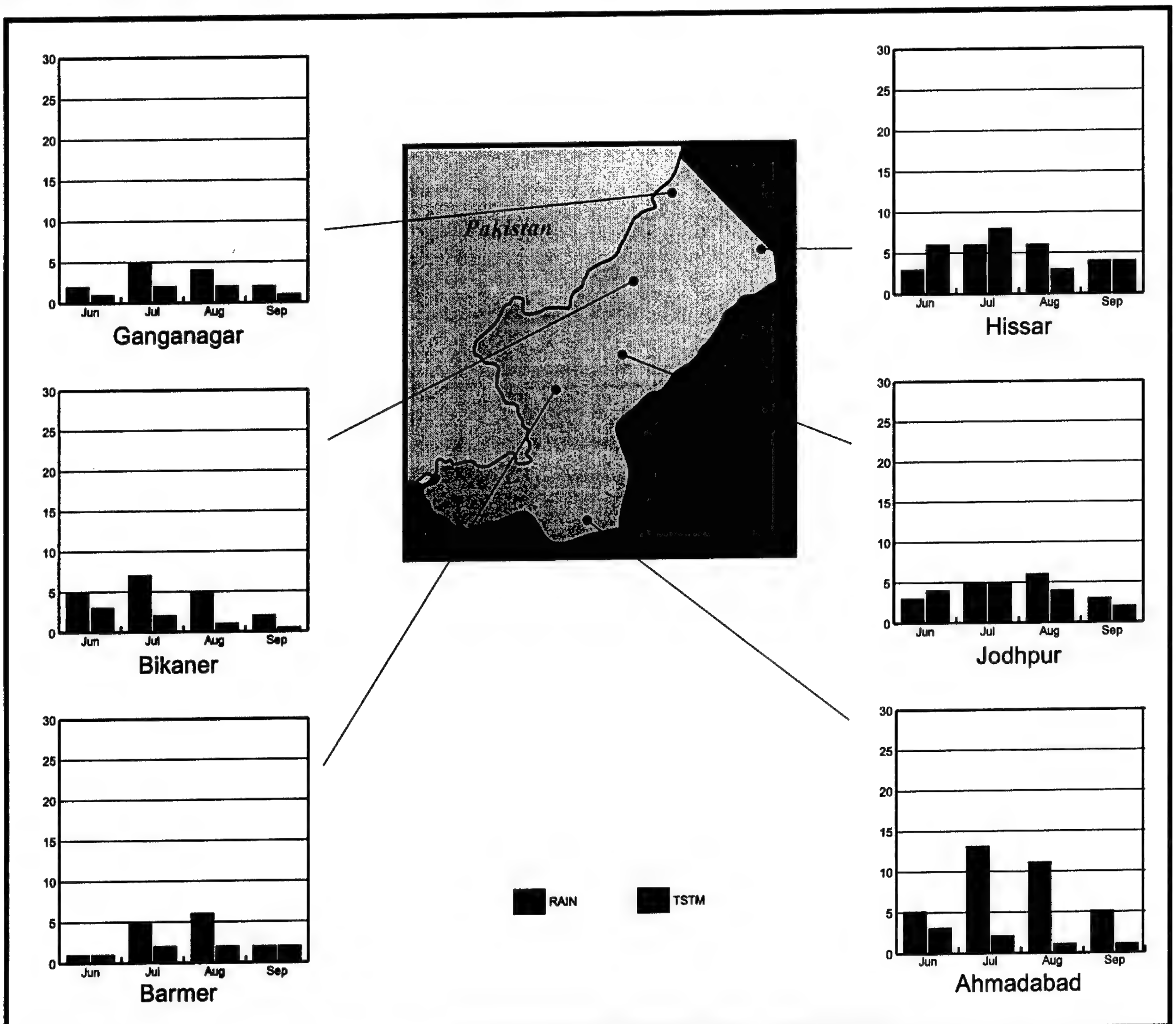


Figure 5-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. The highest temperatures occur in the Thar Desert, where the monsoon is the weakest and the cloud cover is the least. The mean low is 77° to 82°F (25° to 28°C), and the mean high is 95° to 105°F (35° to 41°C). Figures 5-25 and 5-26 show the respective July mean maximum and minimum temperatures. The extreme lows are 65° to 70°F (18° to 21°C), and the extreme highs are 105° to 115°F (41° to 46°C). The highest recorded temperature is 122°F (50°C) at Ganganagar. The mean daily range of temperatures over the desert is 20 Fahrenheit (11 Celsius) degrees; over the rest of the region, the temperature range is less than 15 Fahrenheit (14 Celsius) degrees. Relative humidity in the morning averages 60 percent in June and increases to 80 percent by August. In the afternoon, the humidity is 30 percent in June and 45 percent by August.

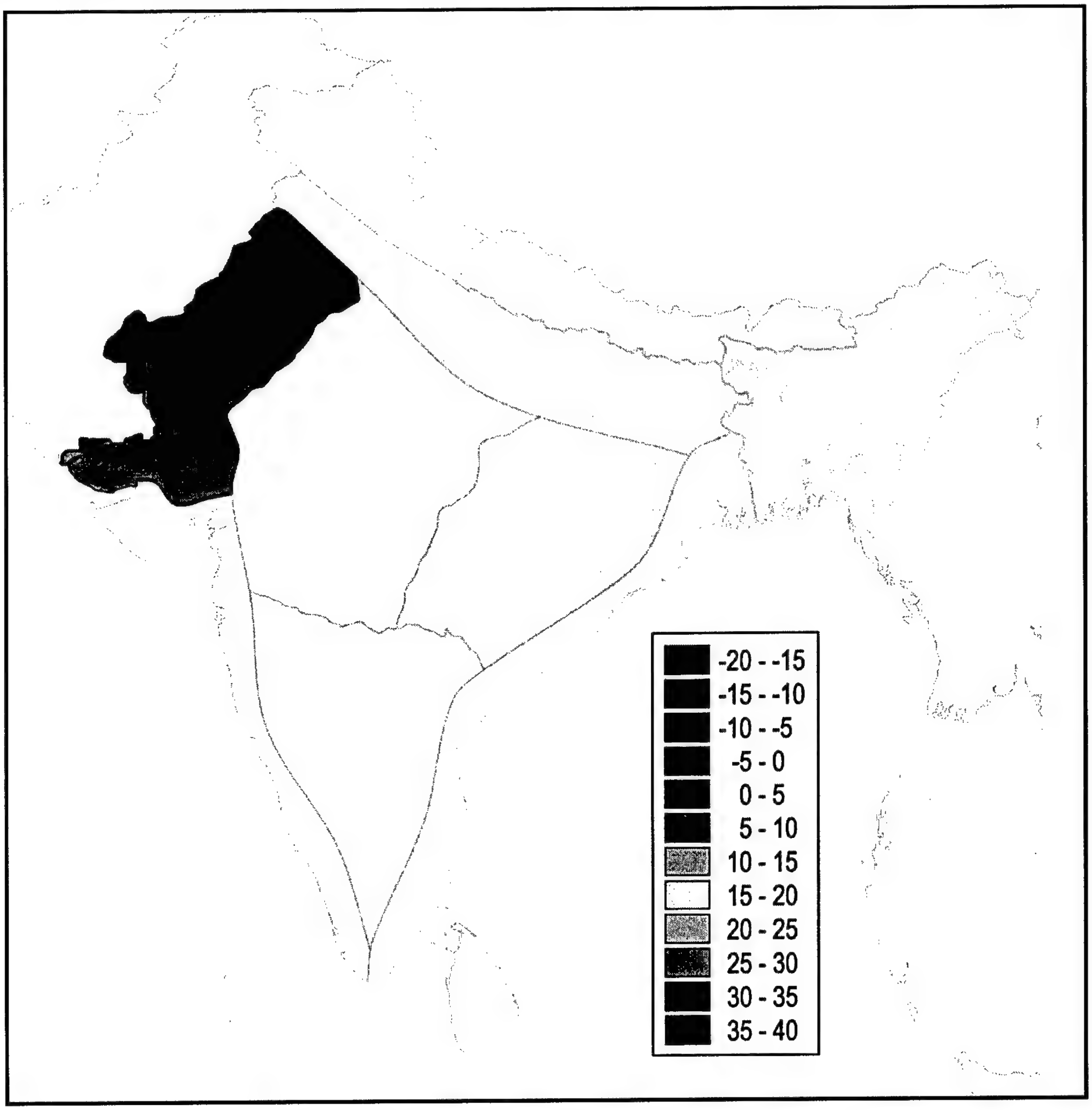


Figure 5-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

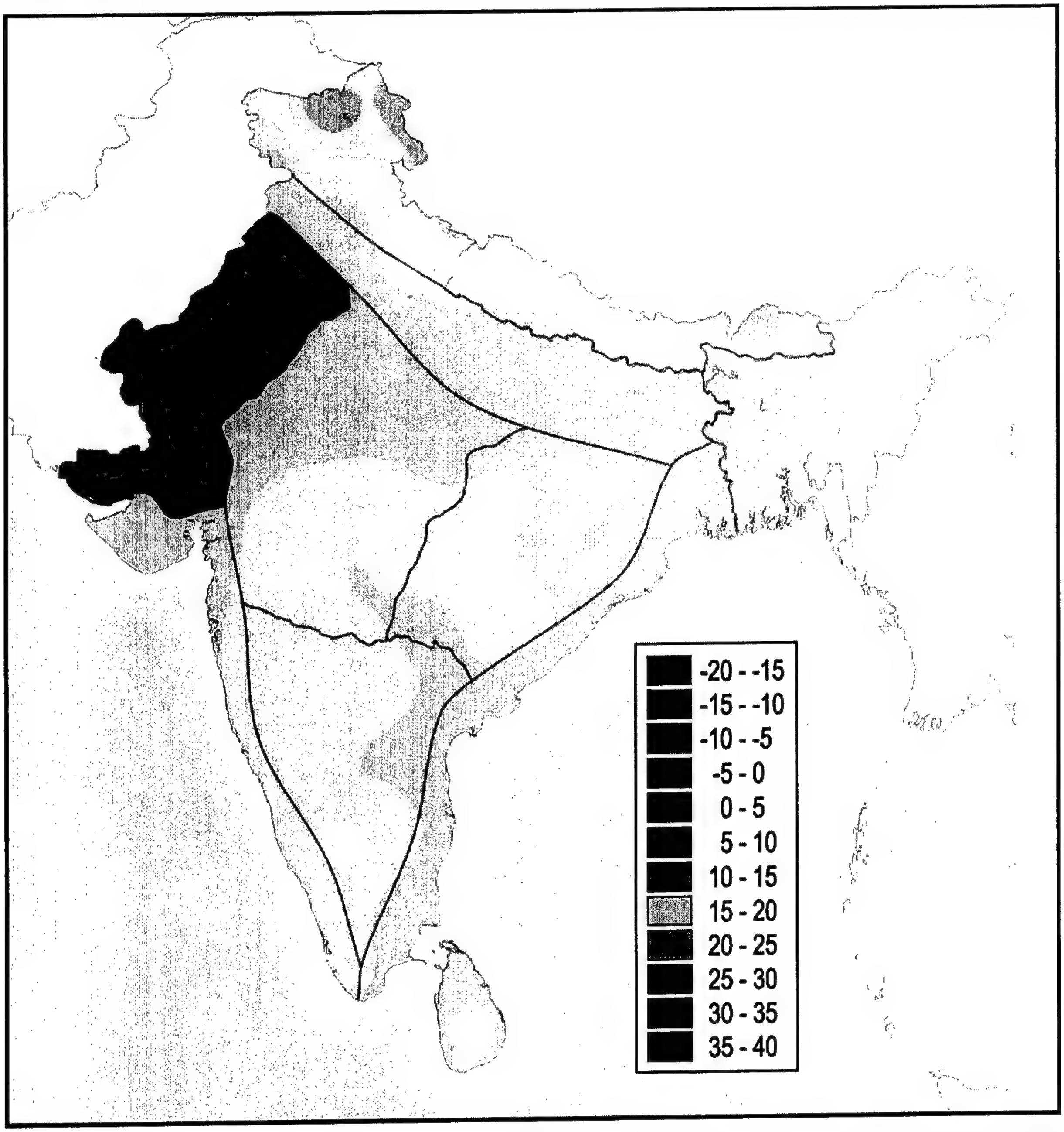


Figure 5-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. Post-monsoon weather is partly cloudy, hot, and dry. Normally, the southwest monsoon retreats in a series of intermittent surges in the first part of September. By mid-October, the monsoonal flow lies well south of northern India. The air mass features during this season are partly hot-weather type and partly of the southwest monsoon type. Occasionally in October and more frequently in November, the modified continental polar air reaches the northwestern portion of the area, sometimes spreading farther south and east under the influence of a western disturbance that travels through northern India. As the surface trough moves south, the high pressure field that was pushed to the northwest rapidly spreads eastward and southward. The dry air circulating around the anticyclone is continental tropical. Dry weather, with high daytime temperatures, but fairly low nighttime temperatures, good to excellent visibility, and light to moderate surface winds, characterize this season.

Sky Cover. Skies are generally clear or partially cloudy. Except for the coastal area and the river valleys, cloudiness is slightly greater during the afternoon than during the early morning and late evening hours. There is a rapid decrease in low cloudiness following the withdrawal of the southwest monsoon. Ceilings less than 1,000 feet rarely occur. Ceilings less than 5,000 feet occur less than 5 percent of the time as seen in Figure 5-27. Ceilings at 5,000-8,000 feet are more frequent, but still not common.

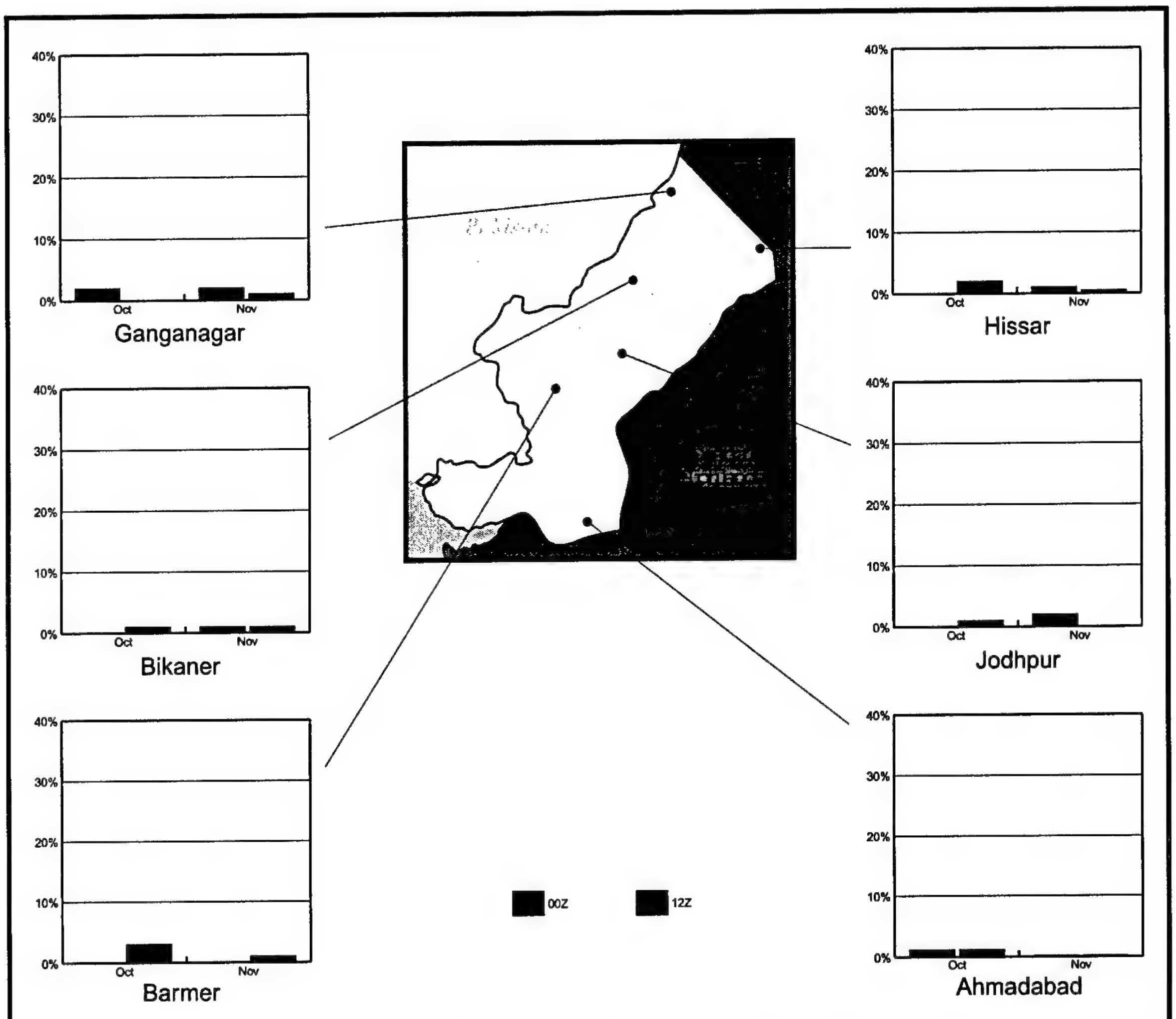


Figure 5-27. Post-Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility below 2 1/2 miles (4,000 meters) in the southern part of the region decreases to less than 4 percent of the time. In the north, visibility less than 4,000 meters occurs 10-15 percent in most locations (see Figure 5-28). In Hissar, the rate increases to 27 percent of the time by November. The main reason for this drastic increase in frequency is associated with fog in the Aravalli Range and from a nearby canal. Visibility less than 1 1/4 miles (2,000 meters) rarely occurs. Fog is the primary visibility restriction throughout much of the region, but in the Thar Desert, dust storms and sand storms are the main causes. Dust storms occur infrequently at most locations. The average number of dust storms is 1-2 per month.

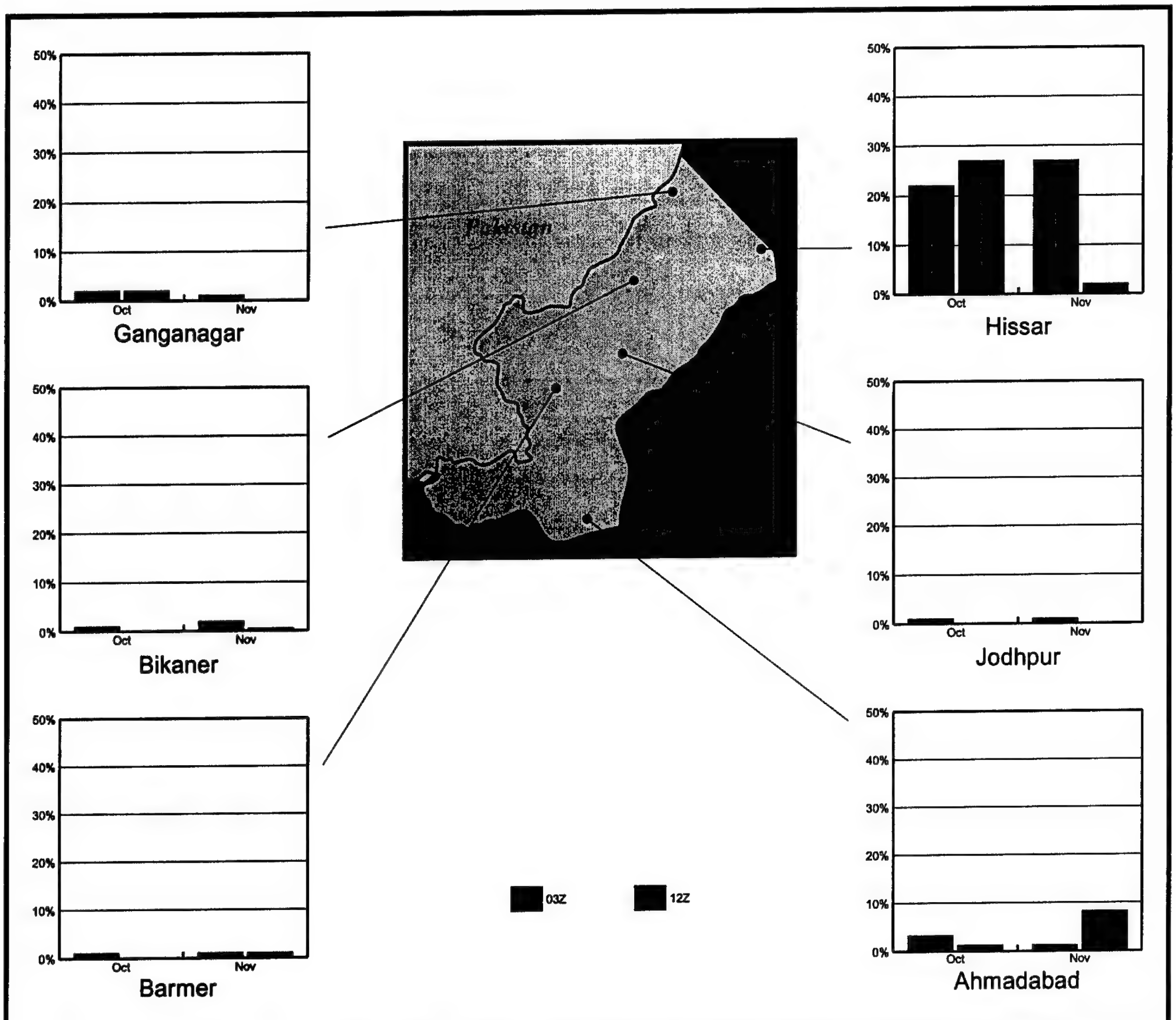


Figure 5-28. Post-Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Light and variable winds prevail over most of the region in October at speeds of 5-10 knots. By November, the winds become northeasterly at speeds less than 10 knots. Dohad experiences stronger funneled winds at an average of 10-15 knots. A land/sea breeze pattern is established on the coast once the ET is well south of the area. At Bhuj, for instance, the winds are from the southwest during the day and from the northeast at night. The sea breeze is usually less than 12 knots. The land breeze is lighter, 7 knots or less. Figure 5-29 shows October wind roses for selected locations in the region.

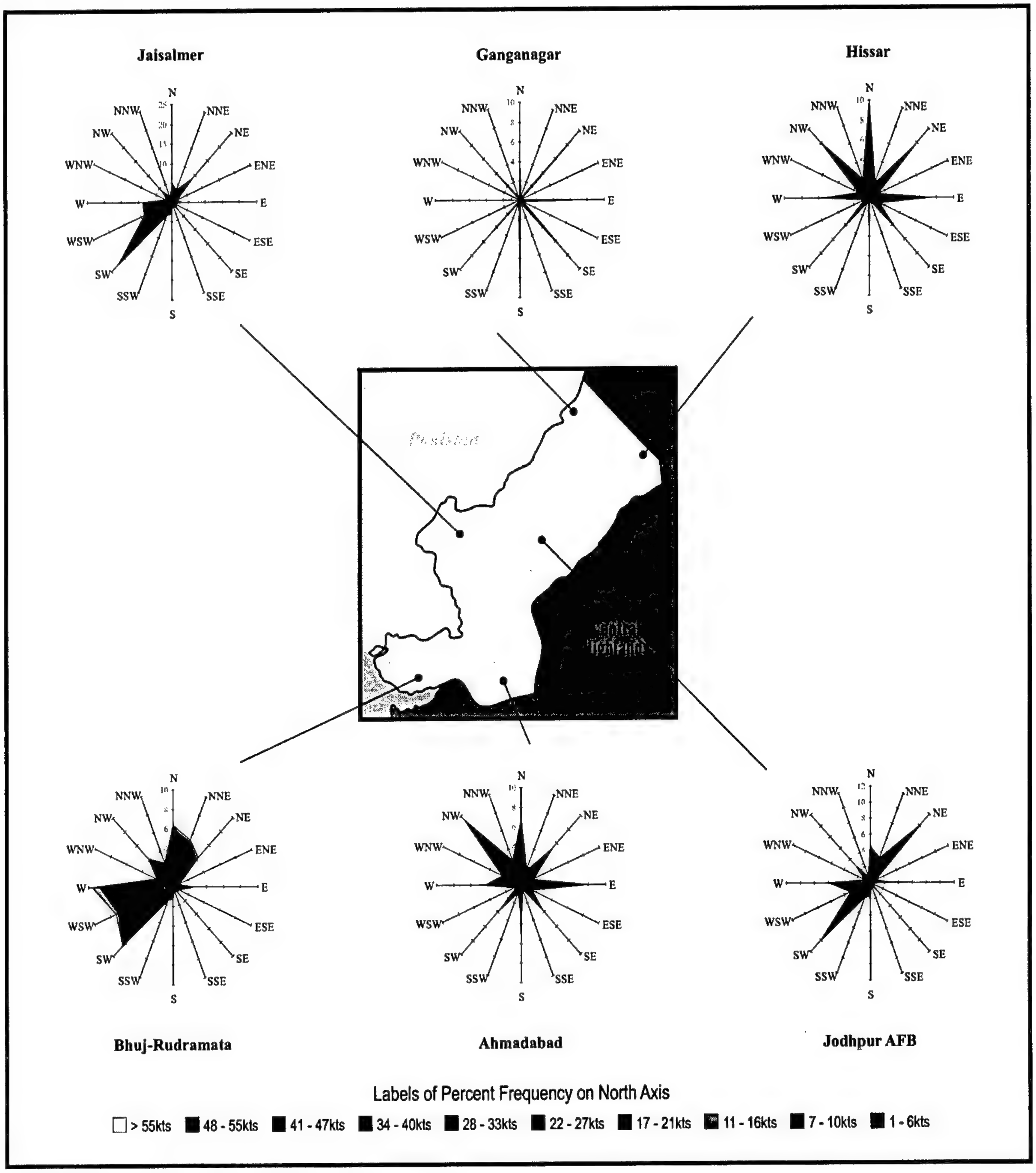


Figure 5-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The upper-air winds are from the northeast and east up to 700 mb. Mean speeds are 15-25 knots. Winds at 500 mb are westerly at 25 knots. Maximum speed may reach 50 knots. The 300-mb winds are also westerly and increase in speed throughout the season. Winds are from the west at a mean speed of 30 knots, with maximum winds up to 60 knots. Figure 5-30 is a composite showing the typical upper-level winds for October over Ahmadabad and Jodhpur.

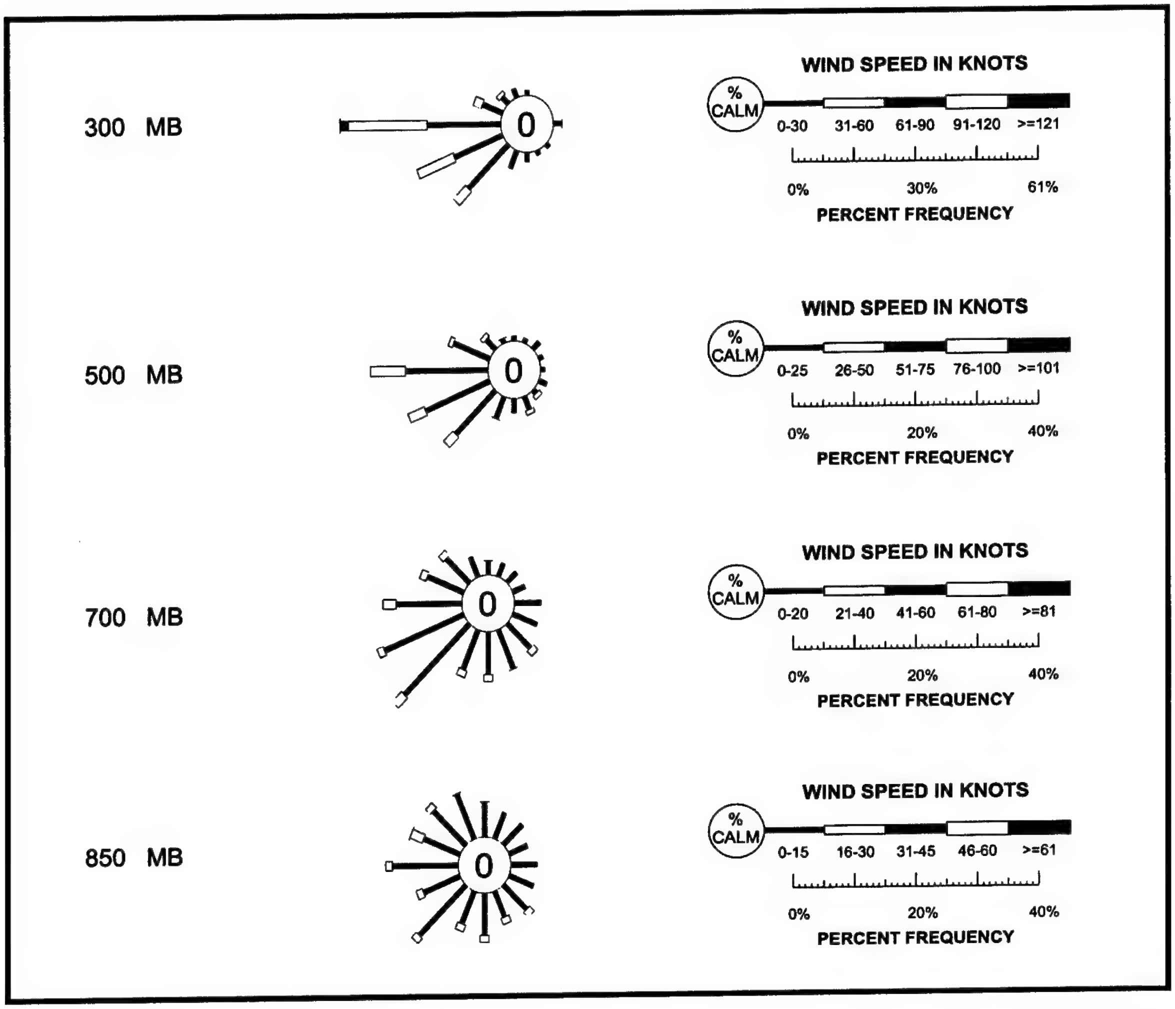


Figure 5-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 and 300 mb over Ahmadabad and Jodhpur.

Precipitation. Following the retreat of the southwest monsoon, dry weather prevails. In general, the average monthly precipitation does not exceed one inch (25 mm). By October, the record amounts of precipitation drop to 3-6 inches (76-152 mm); by November, the maximum is 2 inches (51 mm). The average is only 1-2 rain days per month. Maximum 24-hour precipitation is 5-10 inches (127-254 mm), in September, throughout most of the region then drops to less than 2 inches (51 mm) by November. Most post-monsoon season thunderstorms are associated with convective heating. Most places have one or fewer thunderstorms per month. Severe thunderstorms, hail and tornadoes rarely occur. A storm that produces hail occurs less than once every 5 years. Tornadoes rarely occur. Figures 5-31 and 5-32 show the October mean precipitation amounts and seasonal precipitation and thunderstorm days, respectively.

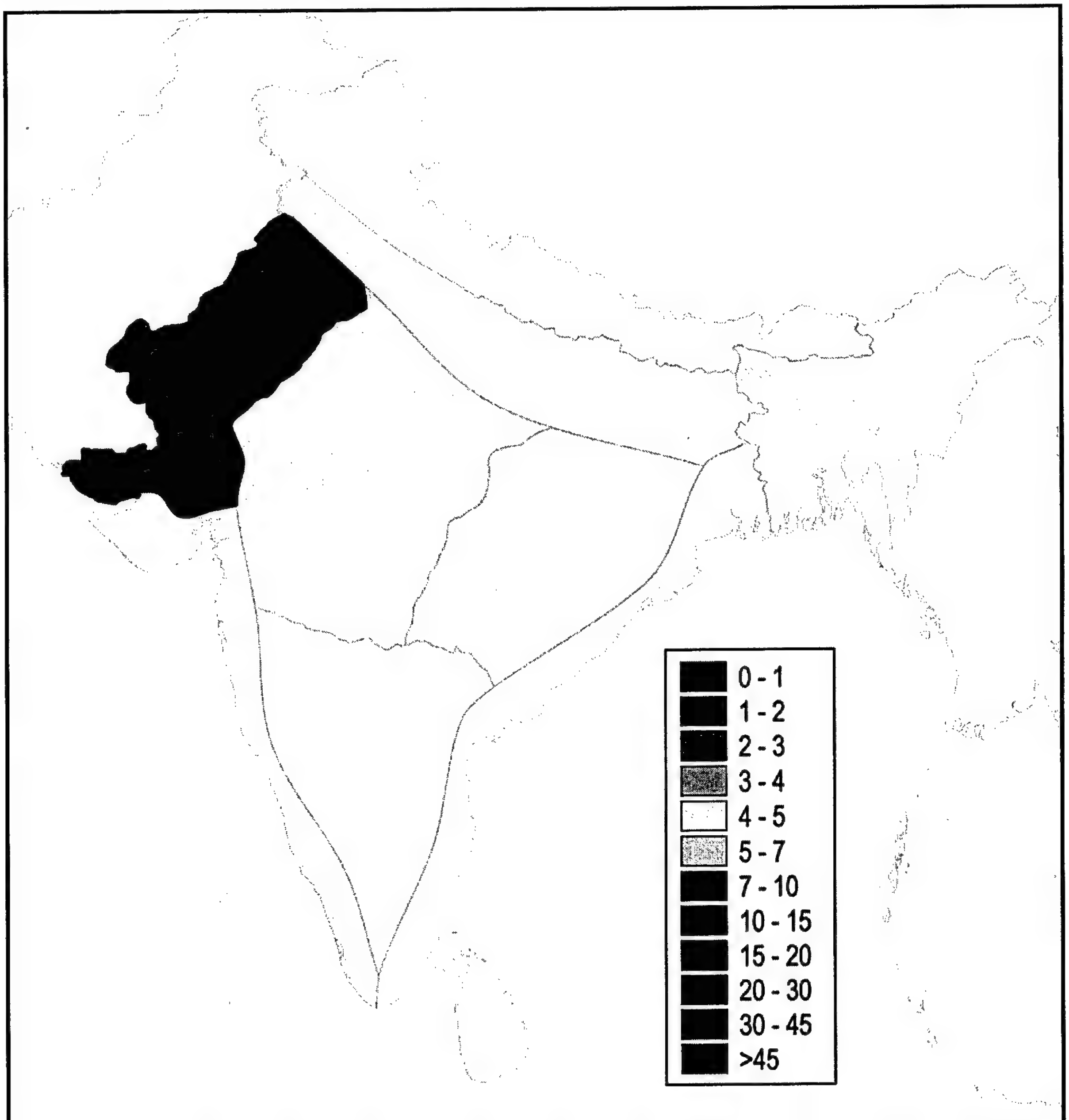


Figure 5-31. October Mean Precipitation (Inches). The figure shows mean rainfall amounts in the region.

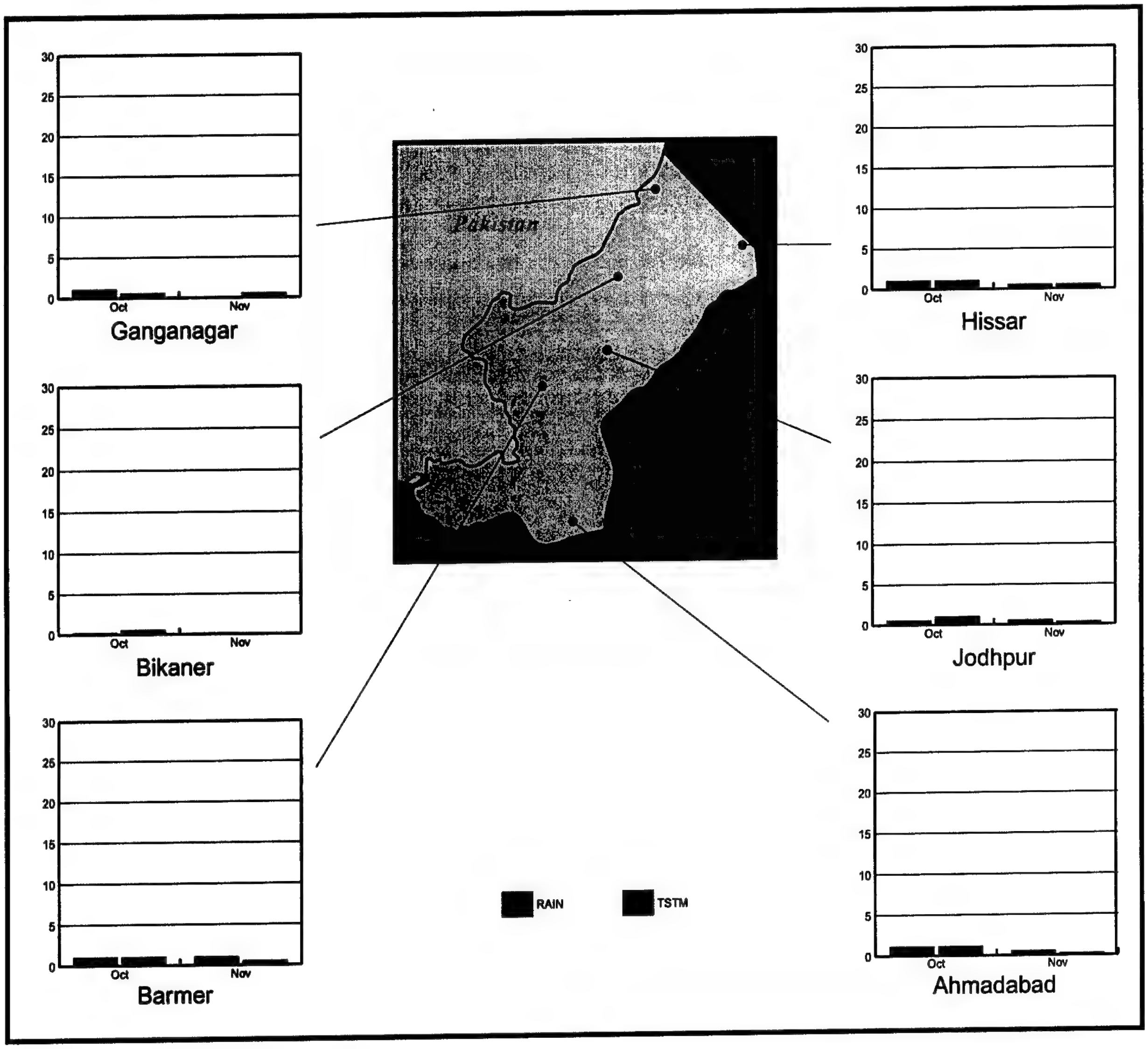


Figure 5-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. After a temporary increase in temperature that often takes place following the retreat of the southwest monsoon, the temperature gradually decreases. The mean low in October is 63° to 70°F (17° to 21°C). By November, it has decreased to 55° to 60°F (13° to 16°C). The mean high in October is 92° to 99°F (33° to 38°C) and decreases in November to 85° to 90°F (29° to 32°C). The extreme low is 30°F (-1°C) in October at Hissar, while the extreme high temperature is 112°F (44°C) in the central Thar Desert. The average diurnal temperature range is 25 Fahrenheit (14 Celsius) degrees. Mean relative humidity in the morning is 65-70 percent. In the afternoon, the humidity decreases from 45 percent in October to 35 percent in November. Figures 5-33 and 5-34 show the respective October mean maximum and minimum temperatures.

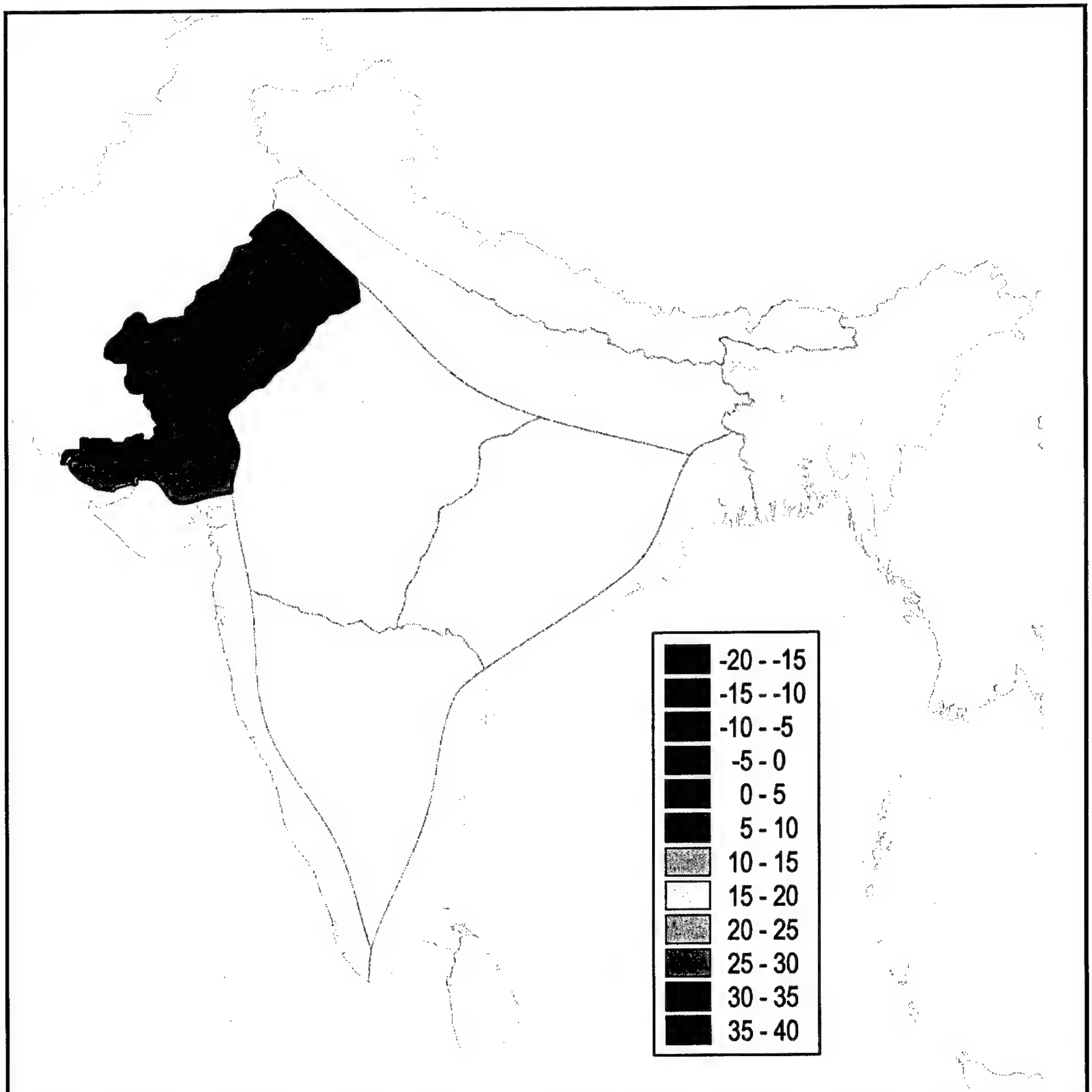


Figure 5-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

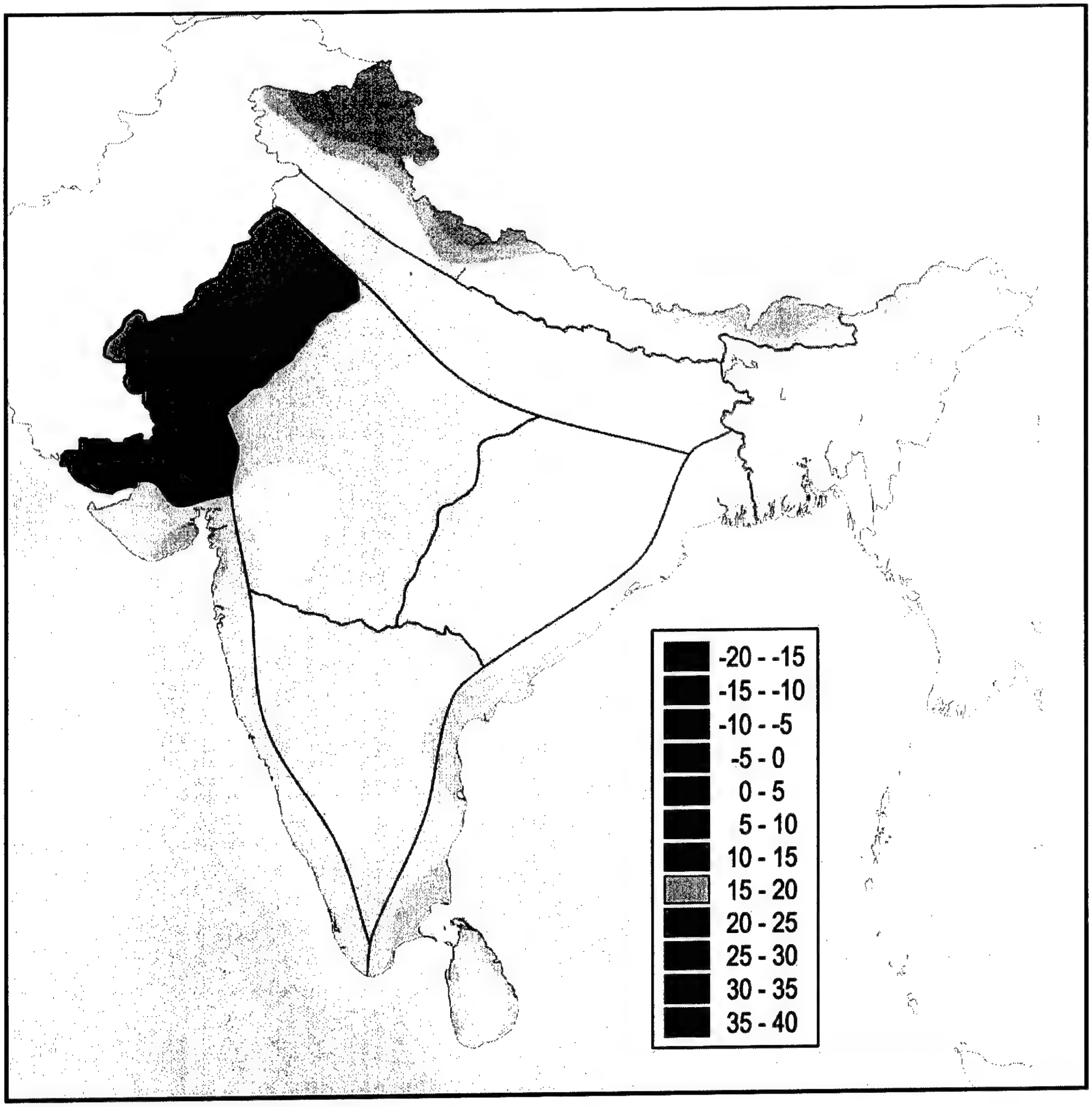


Figure 5-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be lower.

INDO-GANGETIC PLAIN

This chapter describes the topography, major climate controls, special climatic features, and general weather (by season) for the Indo-Gangetic Plain of northern India and southern Nepal.

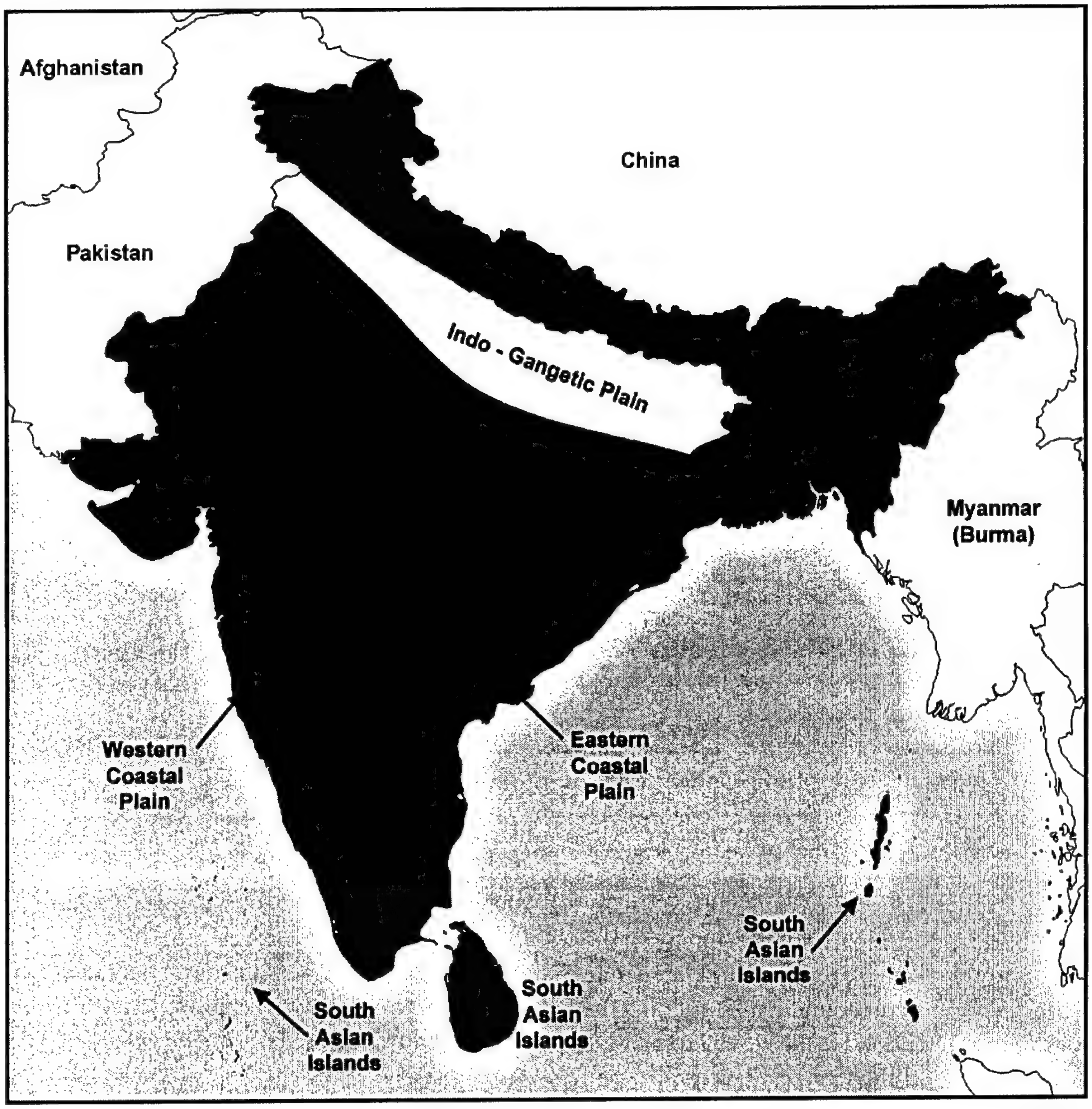


Figure 6-1. Indo-Gangetic Plain. This figure shows the location of the Indo-Gangetic Plain (highlighted in yellow) in relation to the other South Asia zones.

List of Topics

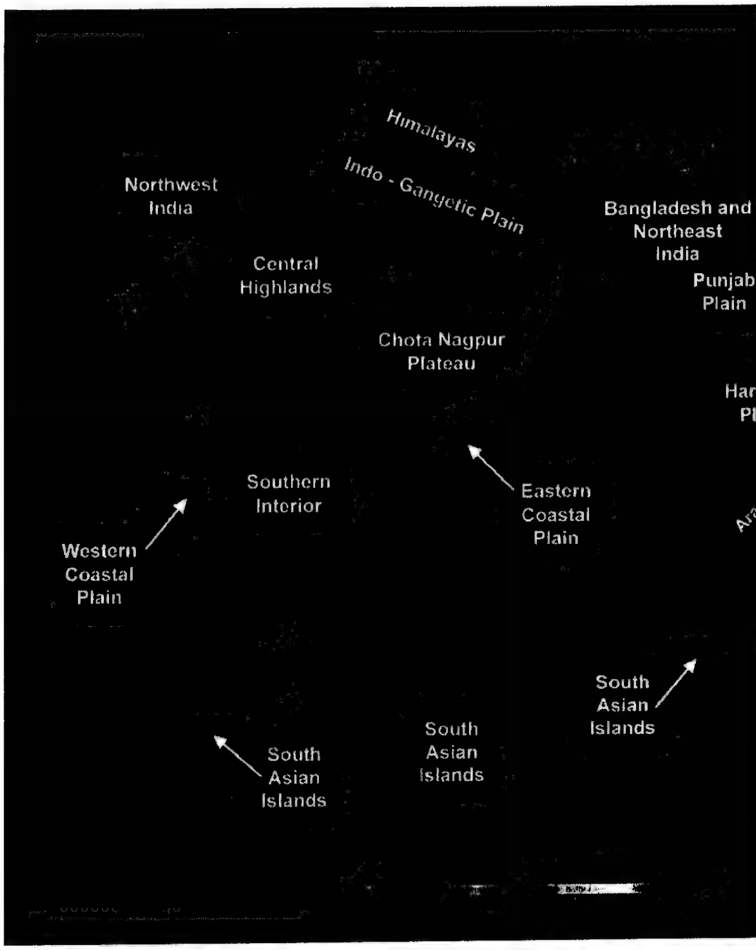


Figure 6-2a. Topography of the Indo-Gangetic Plain.

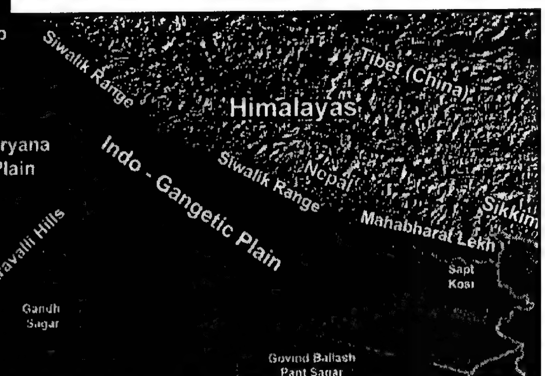


Figure 6-2b. Expanded View of the Topography of the Indo-Gangetic Plain.

Topography

Boundaries. The Indo-Gangetic Plain lies in northern India and southern Nepal along the base of the Himalayan mountain range between Pakistan and Bangladesh. The southern boundary lies along the northern edge of the Thar Desert in the west, the southern edges of the Yamuna and the Ganges River valleys in the center, and along the northern rim of the Chota Nagpur plateau in the east. The Indo-Gangetic Plain is flat except for some scattered hills along the India-Nepal border. These hills have elevations under 2,000 feet (600 meters). The Indo-Gangetic Plain has a gentle, downward slope from north to south and west to east. The average elevation of the plain is 150-1,000 feet (50-300 meters). The highest elevation is along the base of the Himalayas, the lowest in the eastern plain. Small lakes dot the plain.

Rivers and Drainage Systems. Rivers and streams lace the plain. Most start in either the Himalayas or on the Chota Nagpur Plateau, flow east, and merge with the Ganges or Yamuna Rivers. In the foothills of the Himalayas, torrential rains turn many of the gorges and valleys into waterways. A discussion on some of the rivers follow.

Sutlej River. This river originates in southwestern Tibet. It flows westward on its way into Pakistan.

Yamuna River. This river is 860 miles (1,384 km) long and originates in the Himalayas. It flows south, then southeast past New Delhi and merges with the Ganges River at Allahabad. Numerous canals and smaller rivers and streams connect with the Yamuna.

Ganges River. Nearly three quarters of this 1,557 mile (2,505 km) long river lies in the Indo-Gangetic Plain. It originates in the Himalayas and flows southeastward

towards Allahabad. There it meets the Yamuna River, flows eastward into Bangladesh, and empties into the Bay of Bengal. The Ganges has many tributaries and canals.

Gandak River. This 475 mile (764 km) river is formed in central Nepal. It flows southwestward out of the Himalayas into India, then flows southeastward until it merges with the Ganges near Patna.

Ghaghara River. This 570 mile (917 km) long river has its origin in the Himalayas of western Nepal. It flows southwestward into India, then southeastward until it merges with the Ganges west of Patna.

Son River. This river originates on the Chota Nagpur Plateau of east-central India. It flows into the eastern Indo-Gangetic Plain from the southwest and merges with the Ganges west of Patna.

Major Climatic Controls

Asiatic (or Siberian) High. This strong, but shallow thermal high dominates the weather over Asia from November to April. It causes the northeast monsoon as it pushes cold, dry air outwards in all directions. This results in a relatively weak, dry northerly airflow over the region. Outflow from the Asiatic high also creates a trough along the southern slopes of the Himalayas. Lows track along this trough from Europe into northern India.

Equatorial Trough (ET). At its farthest north position, the ET, also known as the monsoon trough, lies along the base of the Himalayas from the Pakistani border to Bangladesh during the southwest monsoon. Its presence is responsible for much of the rainfall during the year. Many monsoon depressions that form in the Bay of Bengal tend to move along it.

Australian High. This thermal high exists during Southern Hemisphere winter. Outflow from this high combines with that of the South Indian Ocean high to help push the (ET) north and initiate the southwest monsoon season. The high also has a role in the development of the tropical easterly jet (TEJ), a feature of the southwest monsoon.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. This high does two different things depending on its strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. The farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe, which use the subtropical jet to zip through the region. When the Indian high is weak it enhances western disturbances.

North Pacific High. This subtropical high is a key player in the South Asian monsoon system. It shifts north and west in May to October, and east and south in November to April. The position of this high is linked to the movement of the ET.

South Indian Ocean (Mascarene) High. This semipermanent high-pressure cell is strongest during Southern Hemisphere winter. It provides cross-equatorial flow from April through October, which helps to form the southwest monsoon flow. The strength of the flow is reflected in the equatorial westerlies and the Somali jet.

Asiatic Low. This thermal low replaces the Asiatic high during Northern Hemisphere summer. It is strongest in July. It helps draw the ET northward and bring southwest monsoon flow to the region.

Australian Low. This thermal low develops over Australia during Southern Hemisphere summer. It breaks up the smooth outflow patterns of the South Pacific and South Indian Ocean highs. This disrupts the TEJ, draws the ET south of the equator, and allows the northeast monsoon to return.

India-Myanmar Trough. This trough occurs over the Bay of Bengal during the southwest monsoon. It helps intensify the TEJ over the area and is a preferred location for monsoon depression development.

Elevation. The Himalayas play a major role in the climate of the Indo-Gangetic Plain. During the winter, they protect the region from the cold, arctic air from Asia. In the southwest monsoon season, they force the warm, moist air to deposit most of the moisture along the southern slopes. Seasonal rainfall totals of 35-50 inches (889-1,270 mm) are common for many locations in the northern part of the region.

Special Climatic Controls

Western Disturbances. These are migratory lows that originate in the mid-latitudes and move eastward along the southern base of the Himalayas. They occur between December and April and account for much of the cloudiness and precipitation during the northeast monsoon. The leeside trough determines their tracks. Western disturbances disappear at southwest monsoon onset and do not return until the next winter.

Monsoon Depressions. These are cold-core tropical systems that originate in the Bay of Bengal. They occur during the southwest monsoon season (June to September). Movement is generally towards the west-northwest into peninsular India and, subsequently, the Indo-Gangetic Plain. Heavy rainfall accompanies these systems.

Tropical Cyclones. The remnants of these tropical systems pose the greatest threat to the Indo-Gangetic Plain just before and after the southwest monsoon season (April-May and October-December). The tropical cyclones that threaten the region usually form in the Bay of Bengal and make landfall in the northern part of peninsular India or Bangladesh. A tropical cyclone system may move northwest into the region as it weakens. By the time it reaches the Indo-Gangetic Plain, its winds diminish significantly, but heavy rainfall is still likely. Occasionally, a tropical cyclone in the Arabian Sea makes landfall on the Rann of Kutch on India's west coast. The remnants of this system may eventually move over the western or central part of the region with light to moderate rainfall.

Nor'westers. These severe thunderstorms affect the region during the hot season (March-May). They can also occur as early as late February and as late as mid-June. Nor'westers are accompanied by strong gusty winds, heavy rainfall, hail, and severe lightning. Tornado development is also possible. Nor'westers generally appear first in the eastern Indo-Gangetic Plain and spread towards the north and west as the season progresses. The storms also become more severe as the season progresses. Warm, moist, conditionally unstable air from the Bay of Bengal clashes with cool, dry air from the northeast. The arrival of the southwest monsoon puts an end to nor'westers as the southerly air flow cuts off the cool, dry air from the northeast.

Dust Storms. Although dust storms can occur anywhere in the region at any time of the year, they are common in the Indo-Gangetic Plain during the hot season. They occur most often in the late afternoons (1600L-1800L) about once a week in the central and western part of the region, less often in the east. The soil dries out and becomes barren during the northeast monsoon. The onset of the hot season brings high temperatures and low humidity. When gusty winds occur, loose soil is lifted up carried to great heights. Visibility is greatly reduced--the severity depending on the dryness of the soil and the wind speed. The arrival of the southwest monsoon generally put an end to the dust storms until after the rainy season.

Hazards for All Seasons

Aircraft Icing. Except for the northwestern part of the Indo-Gangetic Plain, the freezing level is generally so high that icing is not much of a threat to aircraft flights below 10,000 feet. Light to occasionally moderate mixed icing can occur above the freezing level. Severe mixed icing occurs in the vicinity of thunderstorms. Severe icing is also found below 10,000 feet in winter in the vicinity of western disturbances in the northwest section of the region.

Turbulence. Mechanical low-level turbulence is generally present in the afternoons throughout the year. It is most pronounced during the hot season between 1000L and 1700L due to intense heating. The vertical extent of the turbulence depends upon location and time of the day. It is generally not found around sunrise, but it can extend to 1,000 feet within one hour and to 4,000 feet within 3 hours of sunrise. CAT has been encountered to at least 6,000 feet over the southeast section of the region, and over 10,000 feet in the central and northwest sections. Turbulence can also be expected in the vicinity of thunderstorms to the tropopause level. It is most severe during the hot season. Moderate to severe turbulence is also likely near the subtropical jet that overlies the areain the winter. In the eastern section of the region towards the middle of the hot season, the surface easterly wind current is overlain by westerlies aloft. At around 3,000-5,000 feet, where the easterly wind gives way to the westerlies, shear turbulence is often experienced. The severity of the turbulence depends upon the degree of change in the wind direction and speed.

Thunderstorms. During the winter and early hot season, thunderstorms develop along the cold fronts that often accompany western disturbances as they move across central India. All of these storms may produce torrential rain, strong wind gusts, violent up and down drafts, turbulence, icing, lightning, and in-cloud hail. Hail seldom reaches the ground; if it does it is usually small, soft, and causes little damage. Thunderstorms also accompany the ET.

Flash Floods. Heavy amounts of rain fall in a very short time during the southwest monsoon. Streams and rivers overflow their banks. Flash floods occur quickly with little or no warning.

Tropical Cyclones. These systems do not pose a direct threat with their destructive winds as they weaken considerably by the time they reach the region. They are, however, still capable of dumping tremendous amounts of rain that can lead to widespread flooding.

Winter

General Weather. The northeast monsoon regime controls the weather. The Asiatic high dominates Asia, and the equatorial trough (ET) is south of the equator. A weak, dry, northerly flow covers the region and a leeside trough lies along the base of the Himalayas. The subtropical jet is located south of the Himalayas. The usual weather for this time of the year is clear skies, low humidity and large diurnal temperature ranges. Winds are generally light and out of the west or northwest. Rainfall is sparse and usually occurs with western disturbances. Severe thunderstorms (Nor'westers) may occur in the eastern part of the region in late February if warm, moist air flows in from the Bay of Bengal.

Sky Cover. Clear skies typically dominate. Ceilings occur 15 percent of the time in the southeast and 20 percent of the time in the northwest. Ceilings below 3,000 feet generally occur less than 10 percent of the time with the highest rate in January (see Figure 6-3).

Ceilings below 1,000 feet occur less than 5 percent of the time anywhere in the region. Clouds are predominantly altocumulus and cirrus with bases generally above 9,000 feet. Limited cumulus clouds form over the region, mostly in the afternoon or when a western disturbance moves through. Low stratus develops in the early morning hours, particularly over the river valleys. The stratus usually dissipates after sunrise.

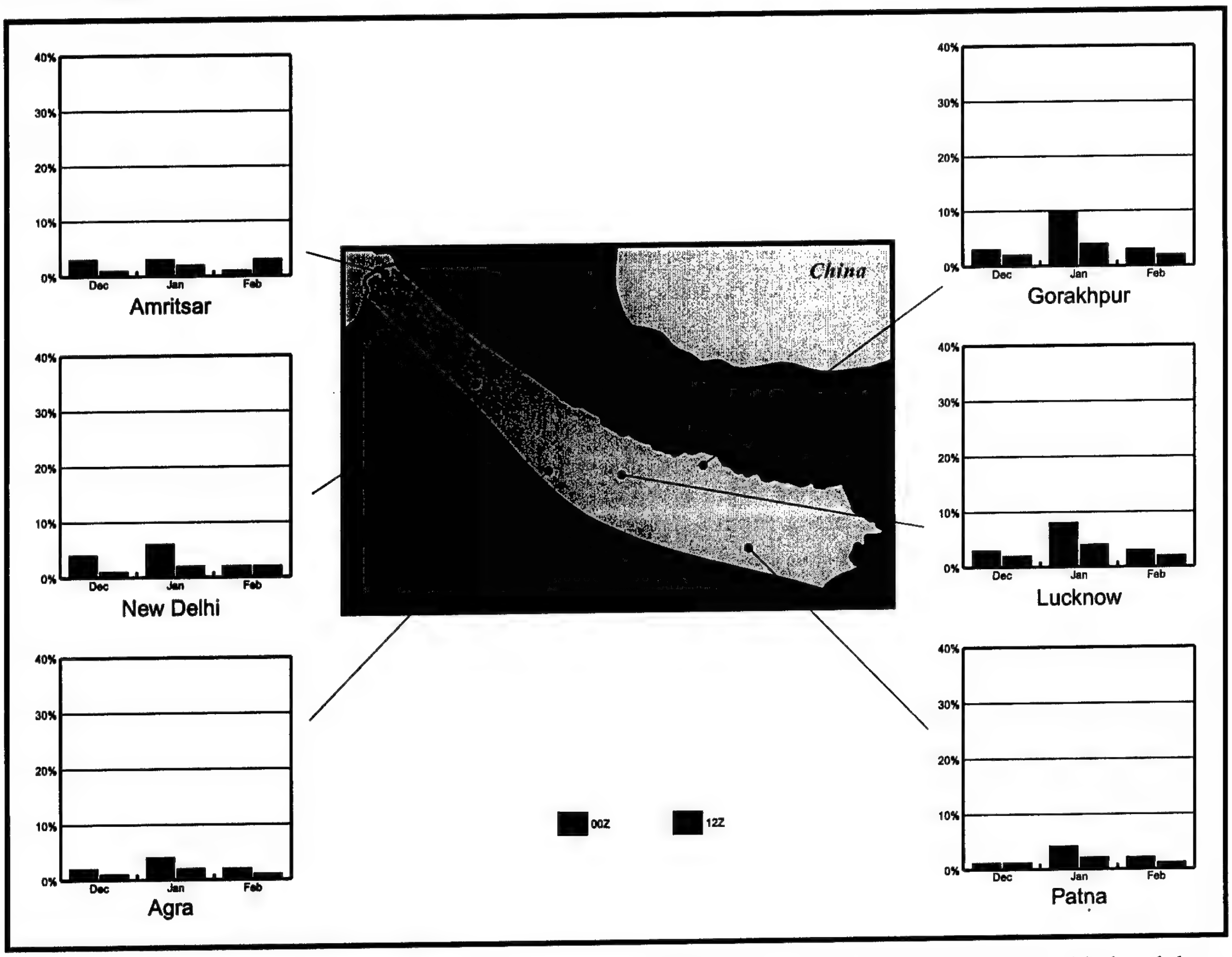


Figure 6-3. Winter Percent Frequency of Ceilings below 3,000 Feet. These graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location at diurnal influences.

Visibility. Visibility restrictions are common. Many locations report an obstruction to visibility in up to 80 percent of the observations taken. These obstructions include rainfall, fog, haze, smoke and blowing dust. Haze and smoke play the biggest role in reducing visibility, followed by fog, rainfall and blowing dust. Visibility below 6 miles (9,000 meters) occurs quite often at most locations. More severe visibility restrictions of less than 2 1/2 miles (4,000 meters) occur less than 40 percent of the time though some locations see this restriction up to nearly 90 percent of the time, especially in the afternoon. Figure 6-4 shows the mean monthly frequency of occurrence with visibility below 4,000 meters at some regional locations. Visibilities below 1 1/4 miles (2,000 meters) occur less than 25 percent of the time for most locations. Some locations have this restriction 40 percent of the time. Haze, dust, and smoke are usually responsible for the restrictions in the afternoon, while a mixture of fog and smoke affects visibility in the morning hours. Visibility restrictions are worst around industrial cities.

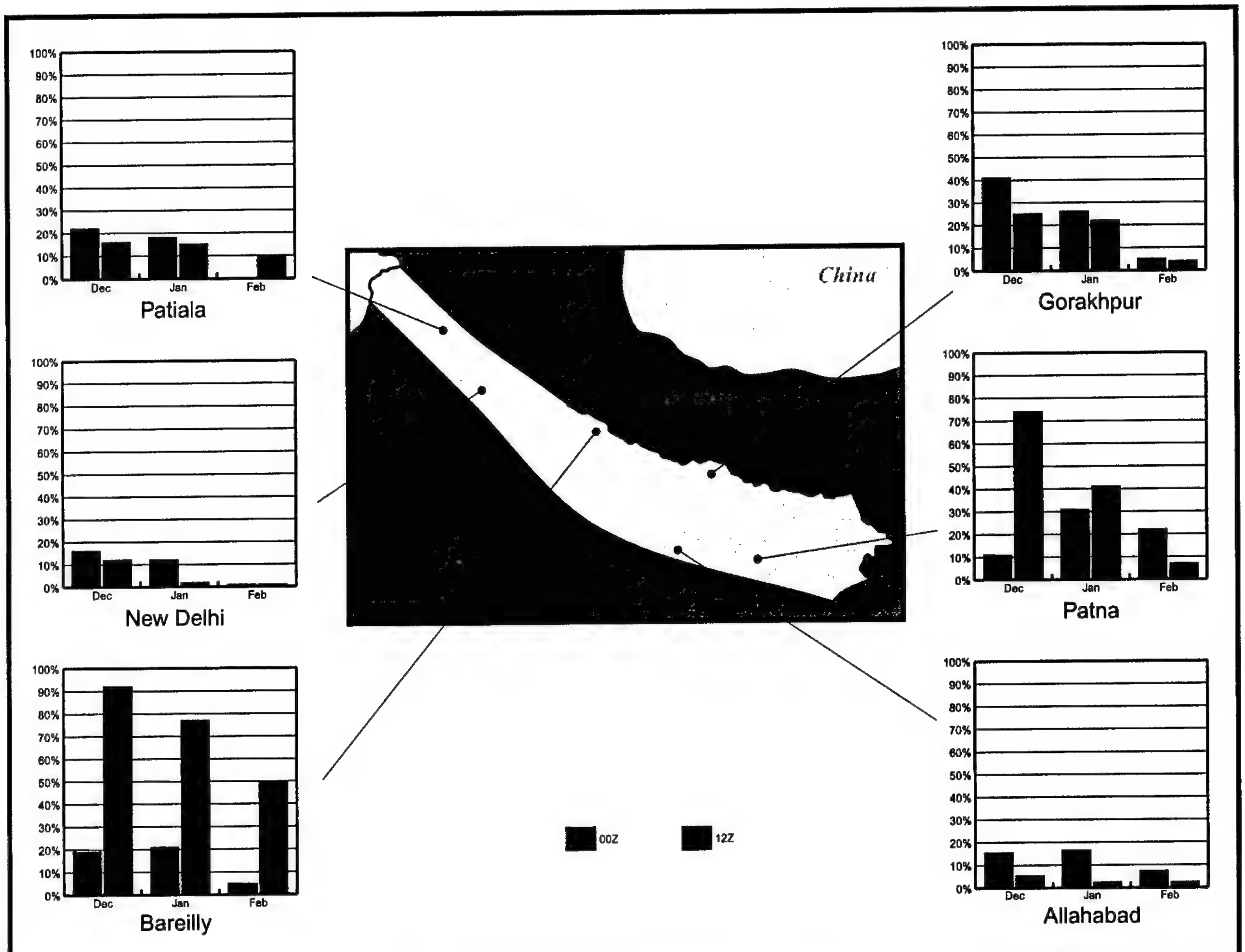


Figure 6-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). These graphs show a monthly breakdown of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Light west to northwest winds dominate (see Figure 6-5). The average wind speeds are 4-8 knots. The wind directions and speeds are fairly consistent unless a western disturbance moves across the region. Wind directions and speeds are then dependent upon direction and distance from the low pressure center. Wind gusts up to 90 knots, associated with thunderstorms, have been reported.

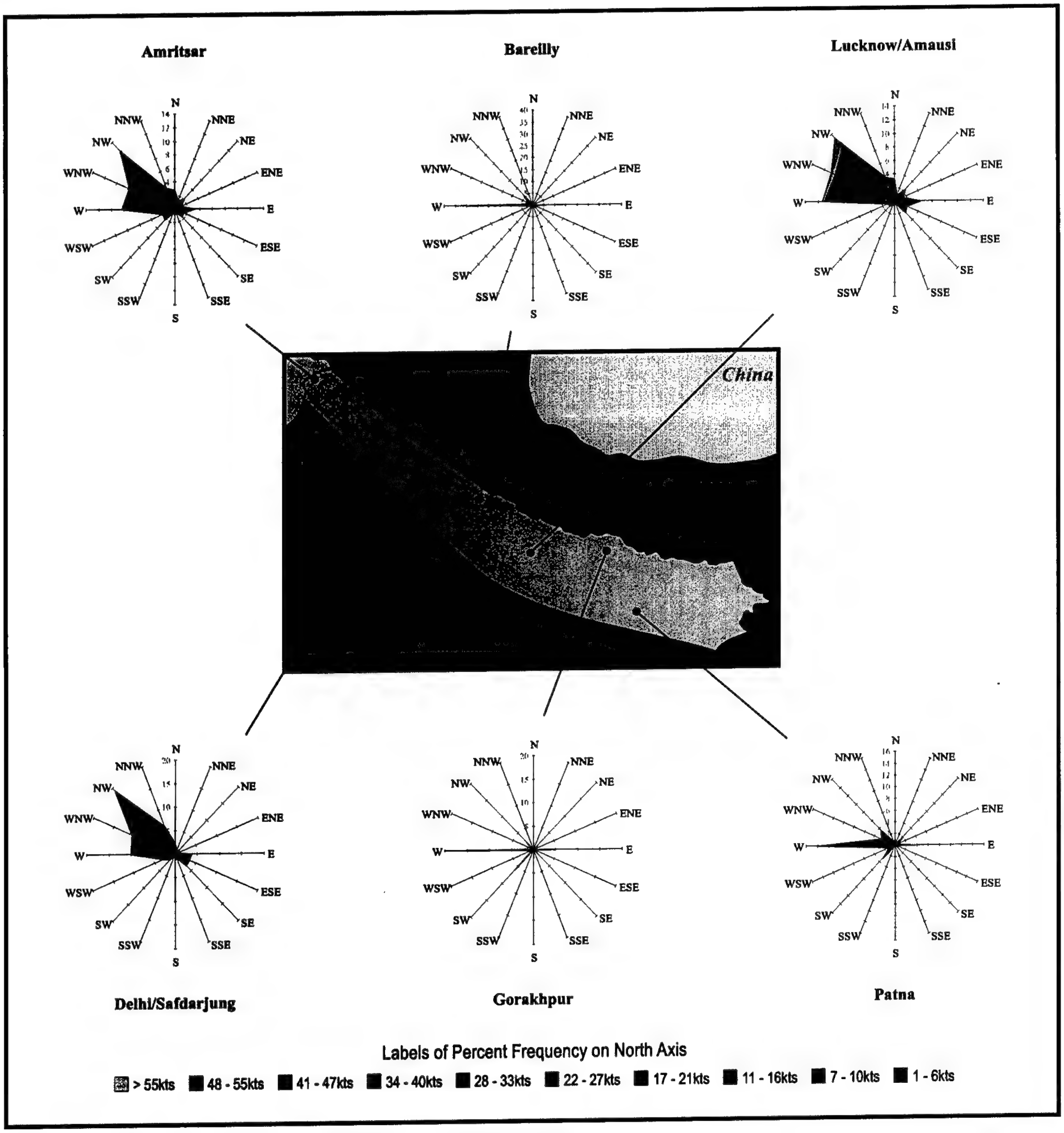


Figure 6-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. West to northwest winds dominate from the surface to 53,000 feet. Wind speeds average 5-20 knots in the first 15,000 feet, then begin to increase dramatically because of the STJ. Wind speeds between 15,000 and 30,000 feet range increase from 35 to 90 knots. The wind speeds peak at 39,000 feet, the level of the STJ, at 80-100 knots. They begin to slowly diminish above 40,000 feet. The winds are strongest in January. Figure 6-6 is a composite of upper-level winds in January over New Delhi and Lucknow.

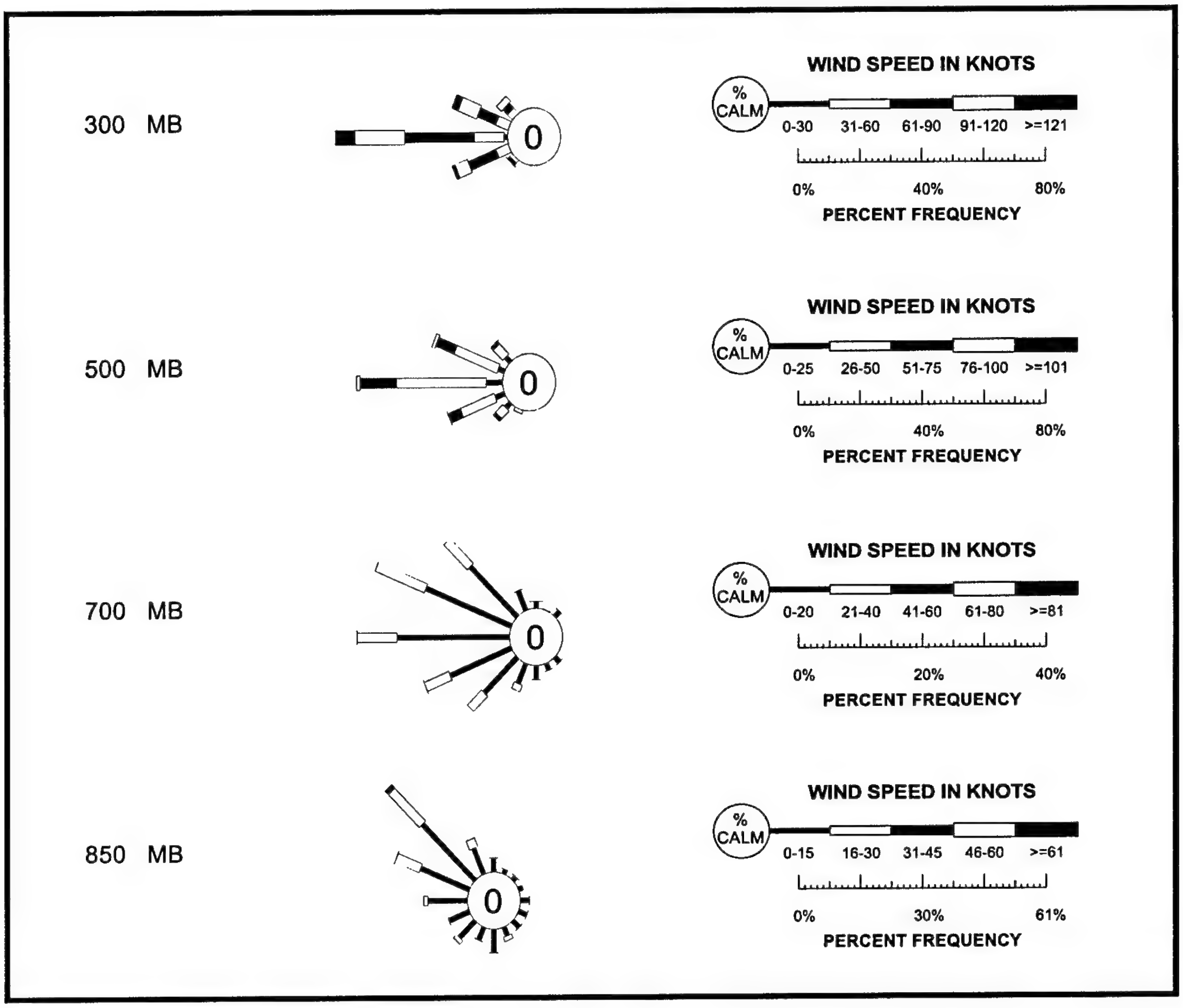


Figure 6-6. January Upper-Air Wind Roses. The composite wind roses depict speed and direction for standard pressure surfaces between 850 and 300 mb at New Delhi and Lucknow.

Precipitation. Rainfall is sparse; most locations receive less than 10 percent of their annual total. Seasonal totals range from near 4 inches (102 mm) in the northwest to an inch (25 mm) or less in the southeast. Monthly rainfall totals are generally less than one inch (25 mm). See Figure 6-7 for January mean precipitation amounts. The extreme monthly amounts range from nearly 4 inches (102 mm) to just over 9 inches (228 mm). The higher amounts occurred in the northwest, the lower in the south and east. The number of days with precipitation and thunderstorms is correspondingly low. Most locations average less than 3 days with precipitation and/or thunderstorms per month (see Figure 6-8). The western disturbances are the primary causes of the precipitation and thunderstorms.

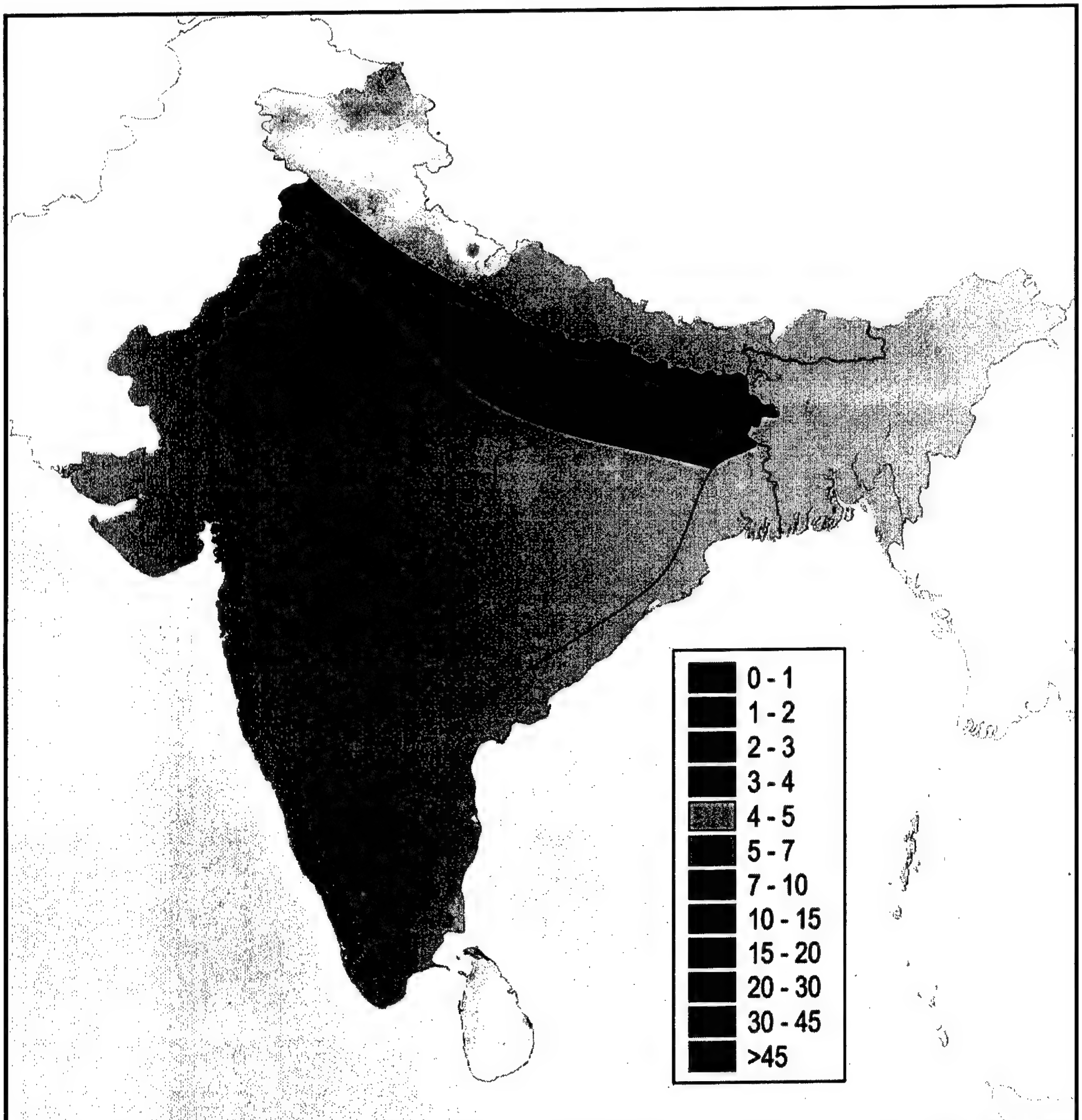


Figure 6-7. January Mean Precipitation (Inches). These graphs depict the mean amount of precipitation received for representative locations in the region.

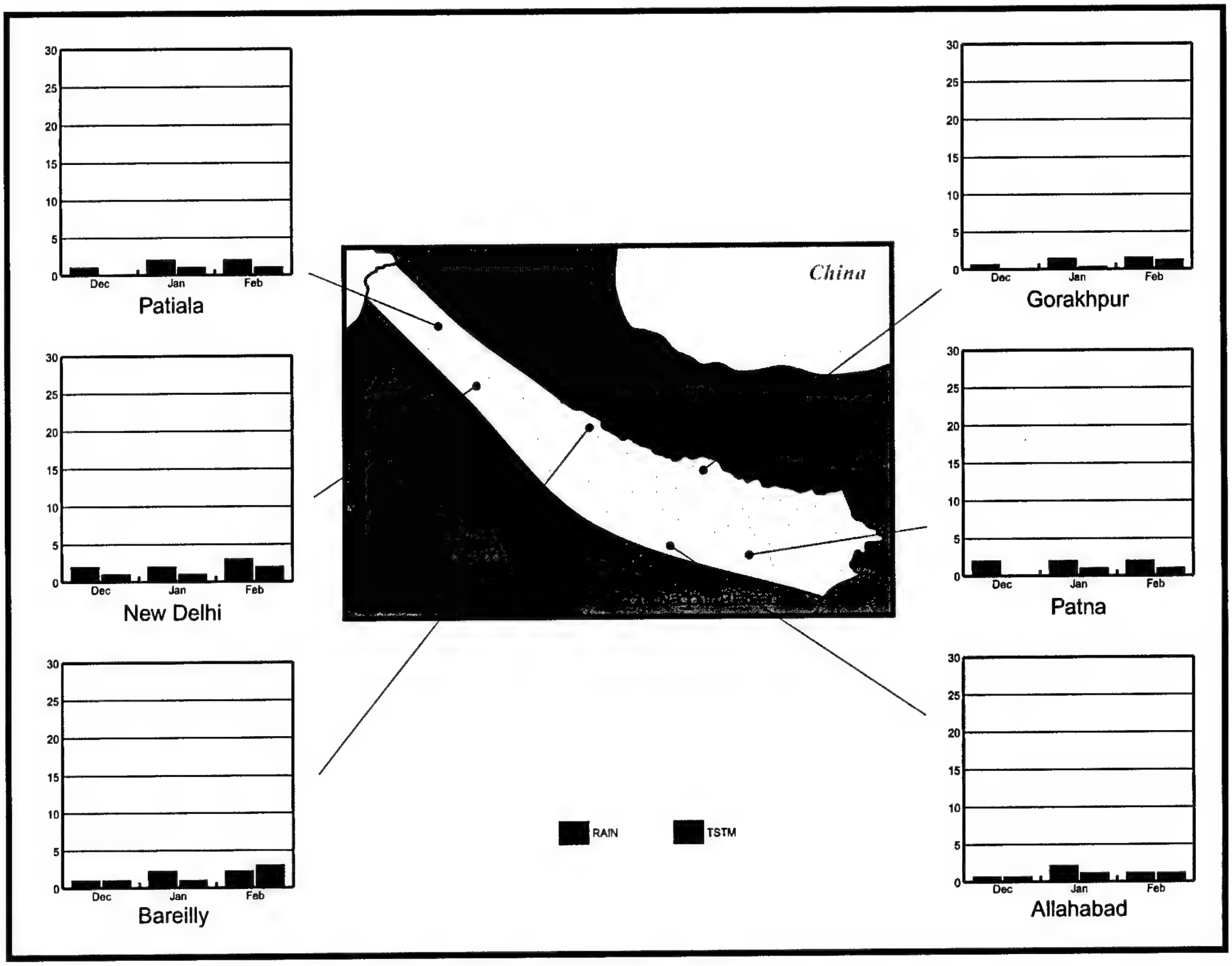


Figure 6-8. Winter Mean Precipitation and Thunderstorm Days. These graphs show the average seasonal occurrence of precipitation and thunderstorm days for representative locations in the region.

Temperatures. Cool temperatures and large diurnal temperature ranges characterize the season. Mean high temperatures range from 63° to 73°F (17° to 23°C) in the northwest to 73° to 79°F (23° to 26°C) in the southeast, as illustrated in Figure 6-9. Mean low temperatures range from 39° to 50°F (4° to 10°C) in the northwest to 48° to 57°F (9° to 14°C) in the southeast. See Figure 6-10. The coolest month is January; February is the warmest. The extreme temperatures reported were 102°F (39°C) and 28°F (-2°C).

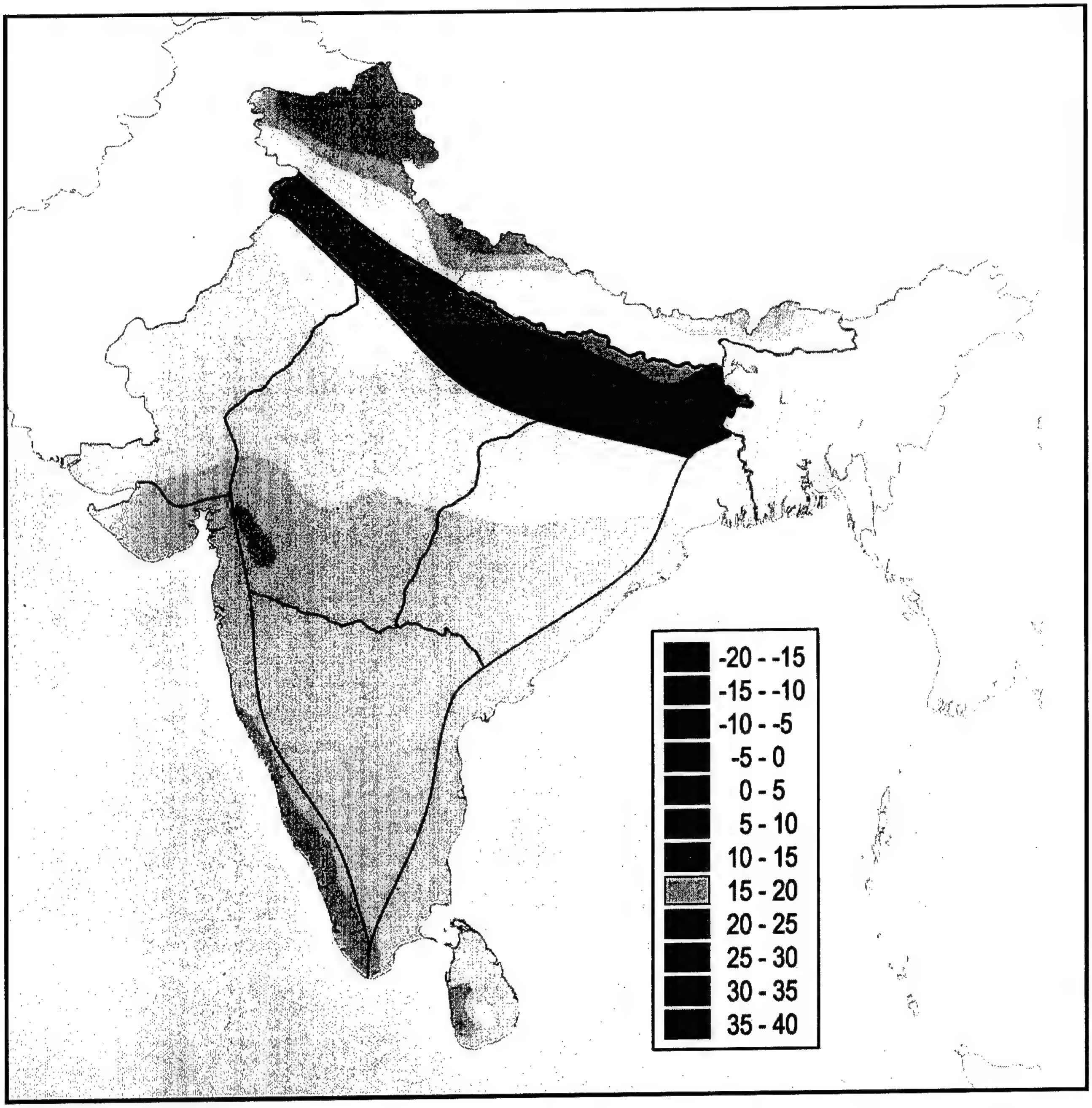


Figure 6-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

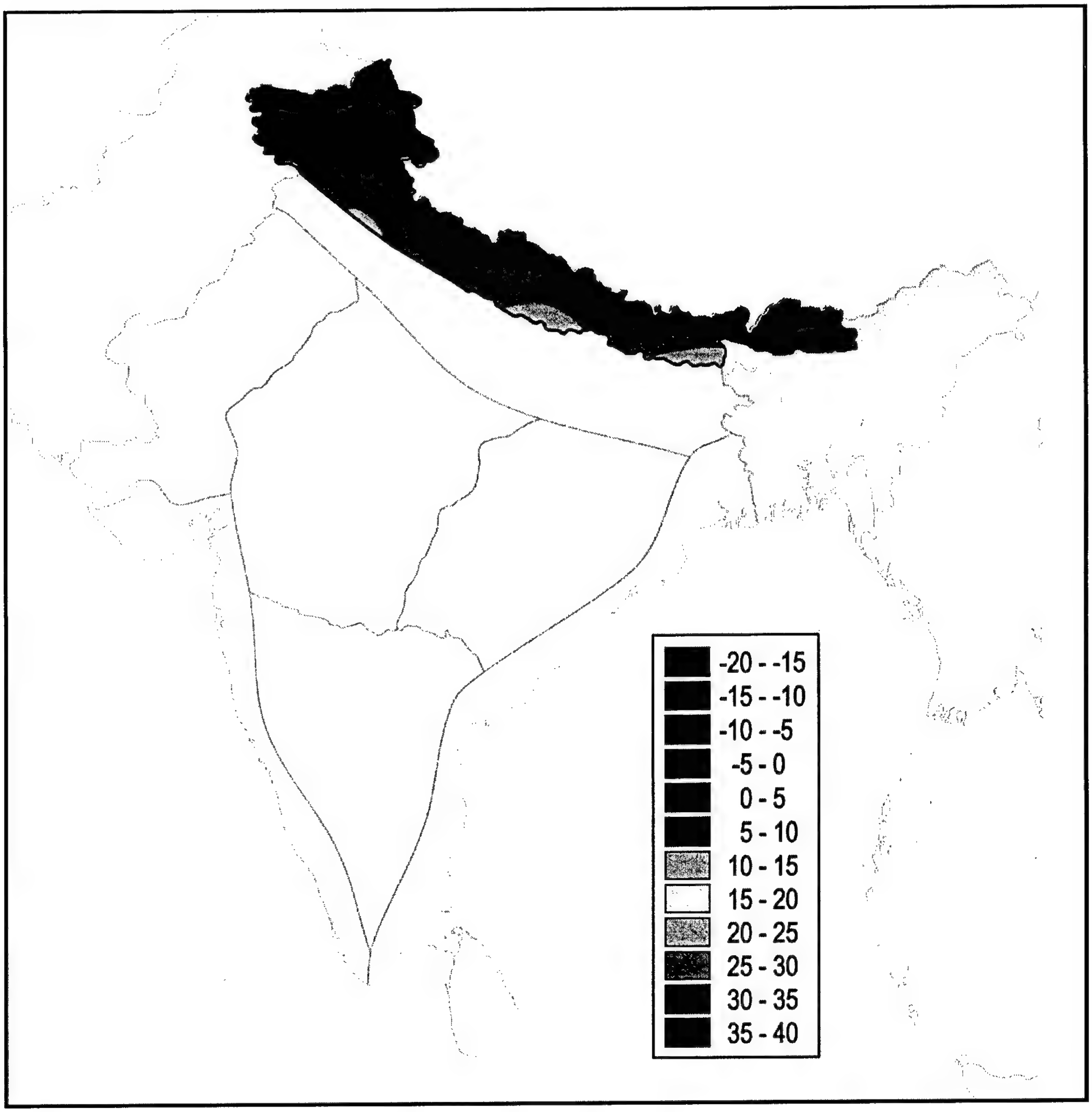


Figure 6-10. January Mean Maximum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often higher than the mean. Mean minimum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

Hot Season

General Weather. The hot season is the transition season between the northeast and the southwest monsoons. The Asiatic high weakens over Asia, and the Asiatic low develops. The STJ begins to move north. The Tibetan high begins to develop while the equatorial trough (ET), still south of India, starts its northward movement.

The hot season is a period of a continuous increase in temperatures. This is due to the development of the thermal low. The air mass associated with the thermal low is tropical continental, which is warm and extremely dry. As the low moves towards the northwest, its air becomes progressively warmer. It undergoes pronounced turbulent mixing and develops a nearly adiabatic lapse rate to considerable height, and a super adiabatic lapse rate below 3,000 feet during the afternoons. As the low intensifies, the occurrence of dust storms increases. As the pressure gradient around the thermal low increases, it combines with the instability present in the lower atmosphere to generate strong gusty winds from midday until evening. The winds pick up loose soil and carry it to great heights. Most dust storms last several hours, but some persist for days. Visibility is greatly reduced in dust storms.

The first of two tropical cyclone peaks begin with the hot season. It is not as active as the post-monsoon season. Activity occurs in both the Arabian Sea and the Bay of Bengal. The remnants of some of the storms that make landfall near Bangladesh make their way into the Indo-Gangetic Plain. Heavy rains from these systems often lead to flooding. Occasionally, an Arabian Sea tropical cyclone makes landfall on the Rann of Kutch. The remnants of this system may eventually move over the western or central part of the region with light to moderate rainfall.

Severe thunderstorm activity also occurs. By the time the Asiatic low sets up, a thermal trough extends east-southeastward across the Indo-Gangetic Plain. The circulation along the trough is such that southerly winds south of the trough bring in warm, humid air from the Bay of Bengal. This moist, unstable air clashes with the cooler, drier air from the northeast, and results in severe thunderstorms (called Nor'westers) over the eastern part of the region. The severe thunderstorms move towards the east-southeast and bring heavy rain, gusty winds, hail and tornadoes. As the hot season progresses, the influx of the moist, unstable air spreads westward. The incidence of severe weather moves westward with the unstable air. The severe weather potential continues until the onset of the southwest mon

Sky Cover. Clear skies are typical. Ceilings occur about 15 percent of the time in the southeast and about 18 percent of the time in the northwest. Ceilings below 3,000 feet generally occur less than 5 percent of the time and are rarely below 1,000 feet (see Figure 6-11). The highest occurrence of low ceilings is in the morning with low stratus. The stratus usually dissipates by mid-to-late morning. Cumulus clouds often develop in the afternoon as a result of thermal heating but usually dissipate by sundown. If sufficient moisture is available, cumulonimbus clouds and thunderstorms may develop.

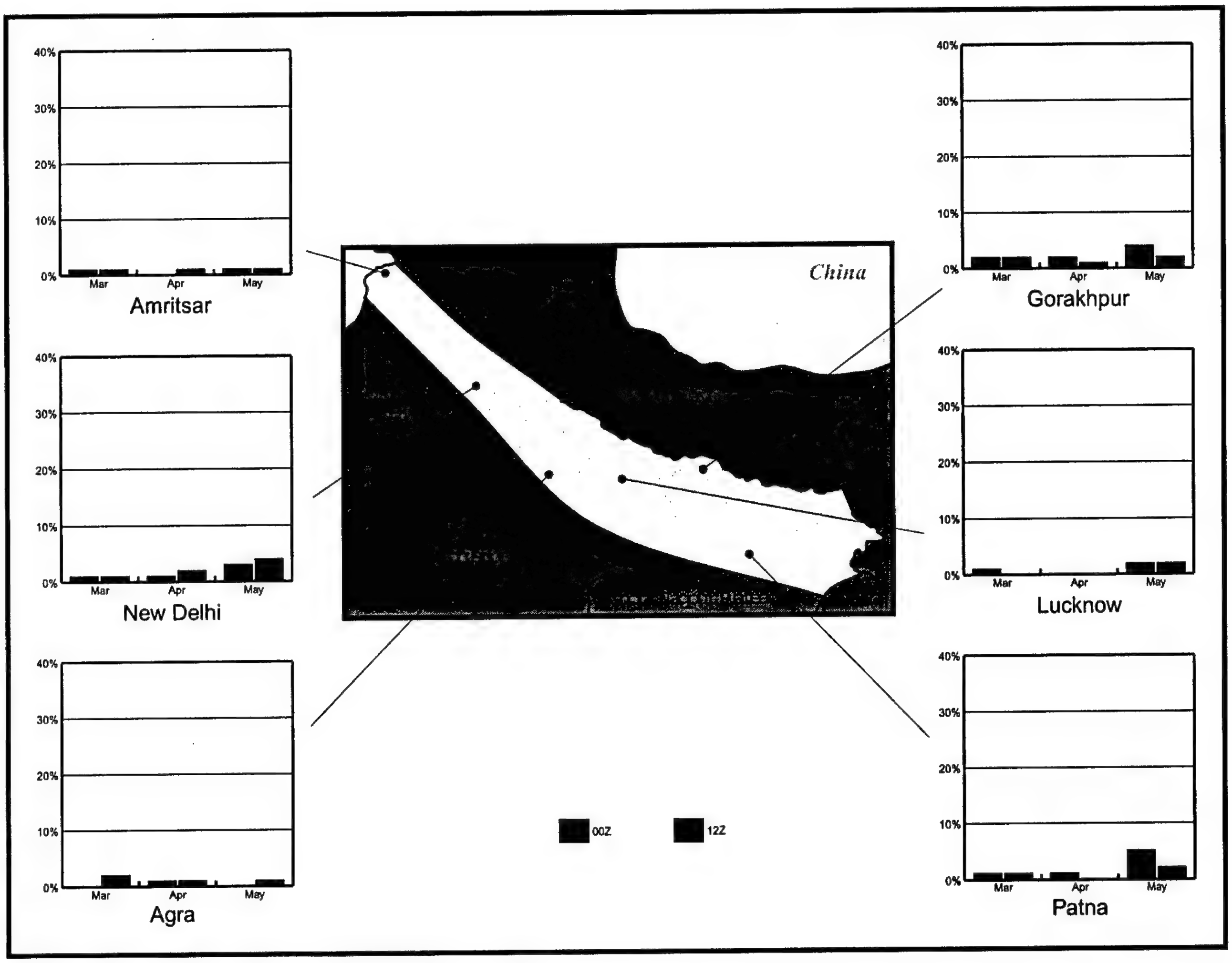


Figure 6-11. Hot Season Percent Frequency of Ceilings below 3,000 Feet. These graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location and diurnal influences. The number in parentheses indicates the GMT to local time conversion factor.

Visibility. Many locations report an obstruction to visibility in up to 65 percent of the observations taken. Visibility below 6 miles (9,000 meters) occurs quite often at most locations. Seasonally, visibility below 2 1/2 miles (4,000 meters) generally occurs less than 30 percent of the time (see Figure 6-12).

Visibility below 1 1/4 miles (2,000 meters) occurs less than 10 percent of the time. Haze and smoke replaces fog as the biggest factor for reduced visibility in the morning hours. Morning fog, however, continues to present a problem along or near a river. Blowing dust or sand becomes a major problem because many locations, especially those in the western half of the region, see very little rainfall. Dust storms are most frequent in the afternoon (1600L-1800L), but can occur at any time. If the dust storm is associated with a dry thunderstorm, the dust is lifted to several hundreds of feet and can become dense enough to prevent the safe takeoff and landing of aircraft. Visibilities below 1/16 mile (100 meters) for periods of several hours are common in major dust storms.

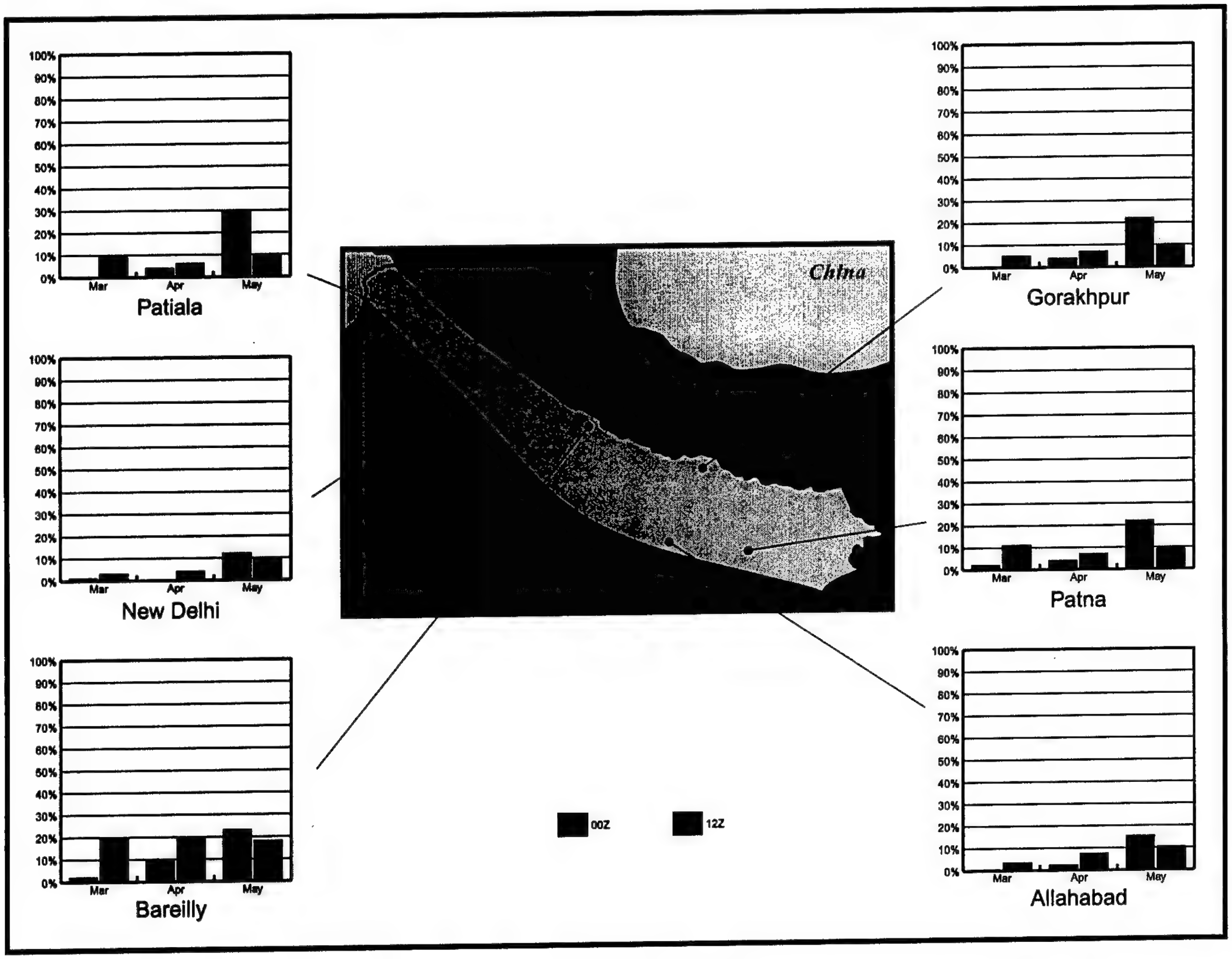


Figure 6-12. Hot Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). These graphs show a monthly breakdown of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. West to northwesterly winds dominate early in the season. In April, the winds shift around to the east in the eastern third of the region (see Figure 6-13). By the end of the hot season, easterly winds dominate the eastern half of the region while west to northwesterly winds continue in the western half. Average wind speeds are 5-10 knots. Wind gusts up to 85 knots, associated with thunderstorms, have been reported.

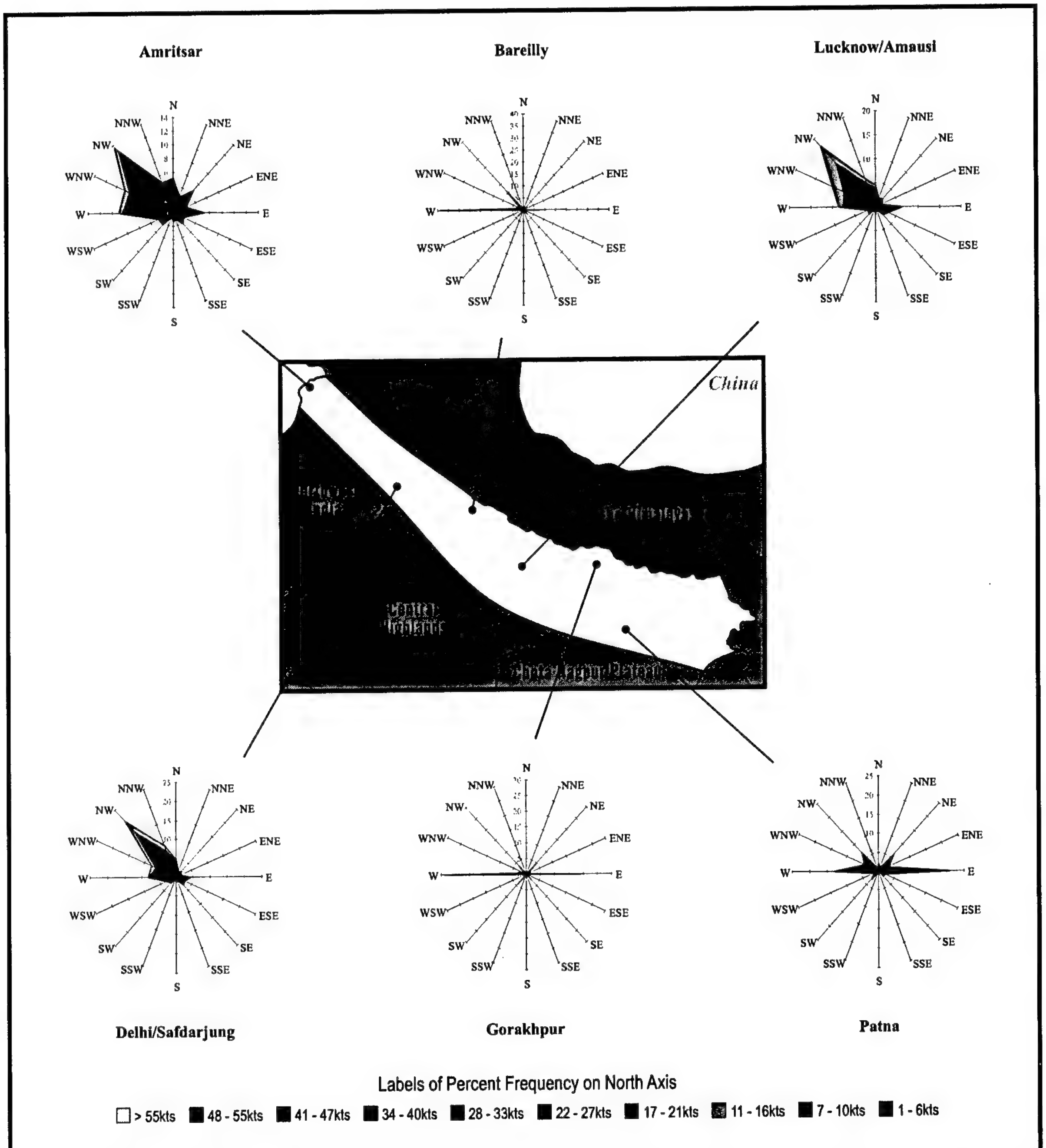


Figure 6-13. April Surface Wind Roses. The figures shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. West to northwest winds are present from the surface to 53,000 feet (see Figure 6-14). Winds average 5-20 knots in the first 15,000 feet, then increase due to the presence of the subtropical jet. Wind speeds increase steadily to about 65 knots by 30,000 feet. The wind speeds peak at 39,000 feet, the level of the subtropical jet, between 80 and 85 knots. They begin to diminish above 40,000 feet. The winds are strongest in March, then begin to diminish as the STJ moves north. By May, it is no longer present over the Indo-Gangetic Plain.

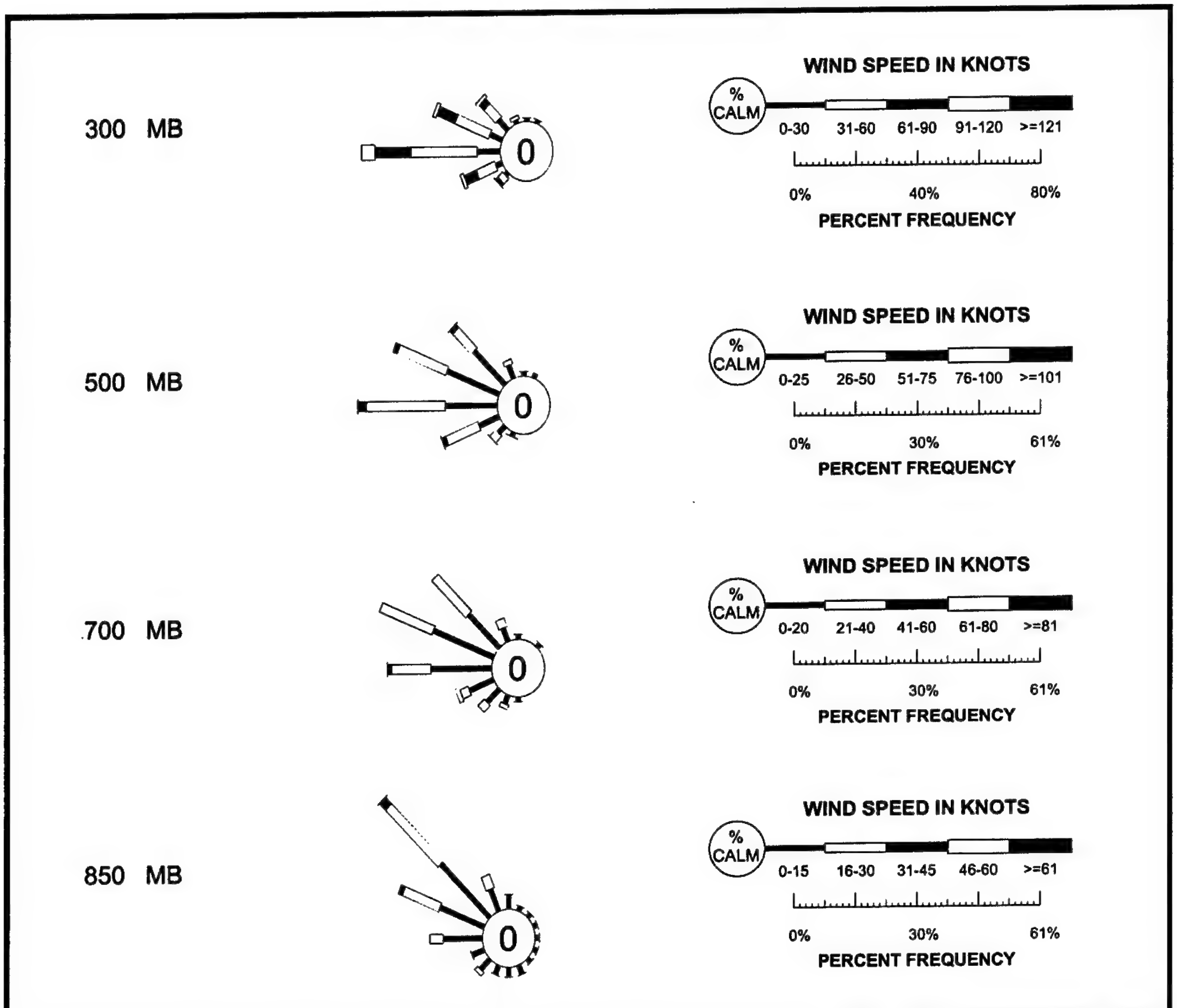


Figure 6-14. April Upper-Air Wind Roses. The composite wind roses depict speed and direction for standard pressure surfaces between 850 and 300 mb at New Delhi and Lucknow.

Precipitation. The hot season is drier than winter for the western two-thirds of the region (west of 83° longitude). Many locations receive one-half up to two-thirds of the rain that falls during winter. March is the wettest month, and April is the driest (see Figure 6-15). Seasonal amounts in the western two-thirds of the region range from less than one inch (25 mm) along the Thar Desert to under 2.5 inches (64 mm) along the base of the Himalayas. Monthly totals are less than an inch (25 mm) at nearly all locations. The extreme monthly rainfall was 4-8 inches (102-203 mm). Western disturbances are responsible for much of the rain in March and April; thunderstorms provide most of the May rain. The number of days with rain is low. All locations have under 4 rain days per month (see Figure 6-16). Thunderstorm activity increases, 2-4 thunderstorm days at most locations each month, but many thunderstorms are dry. Dry thunderstorms induce many of the dust storms in the area.

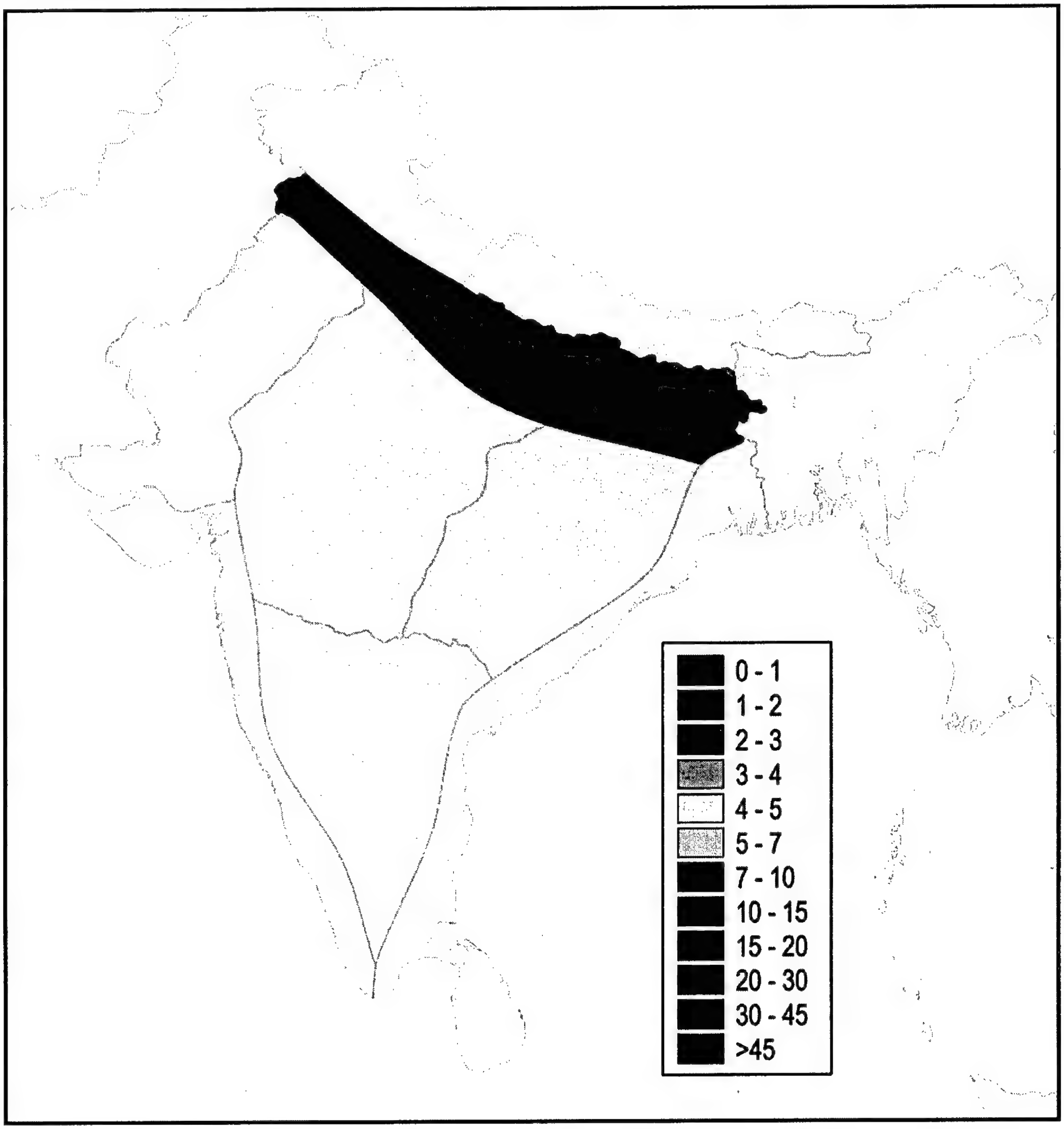


Figure 6-15. April Mean Precipitation (Inches). These graphs depict the mean amount of precipitation received for representative locations in the region.

The eastern third of the region is different. All of the locations in this area receive more rainfall in the hot season than in the winter. Seasonal totals range from nearly 2.5 inches (64 mm) along the Chota Nagpur plateau to over 5 inches (127 mm) along the Himalayas. March and April are fairly dry; most locations report less than one inch (25 mm) of rain each month (see Figure 6-15). The area sees a significant increase in rainfall in May. Most locations see two to three times the amount of rain in May than April with monthly totals up to nearly 3 inches (76 mm). The highest totals are along the base of the Himalayas due to orographic lift. The extreme monthly totals are 5-9 inches (127-228 mm). Some of the heavier rainfall results from tropical cyclones. There is a corresponding increase in the number of days with rain and thunderstorms as the hot season progresses (see Figure 6-16). All locations have less than 3 days of rainfall in March and April. In May, the number of days with rain increases to 3-5 along the Himalayas. The number of thunderstorm days increases from 1-3 in March and April to 2-5 in May. Some locations in the central and southern part of the area, like Patna, have thunderstorms that do not bring rain.

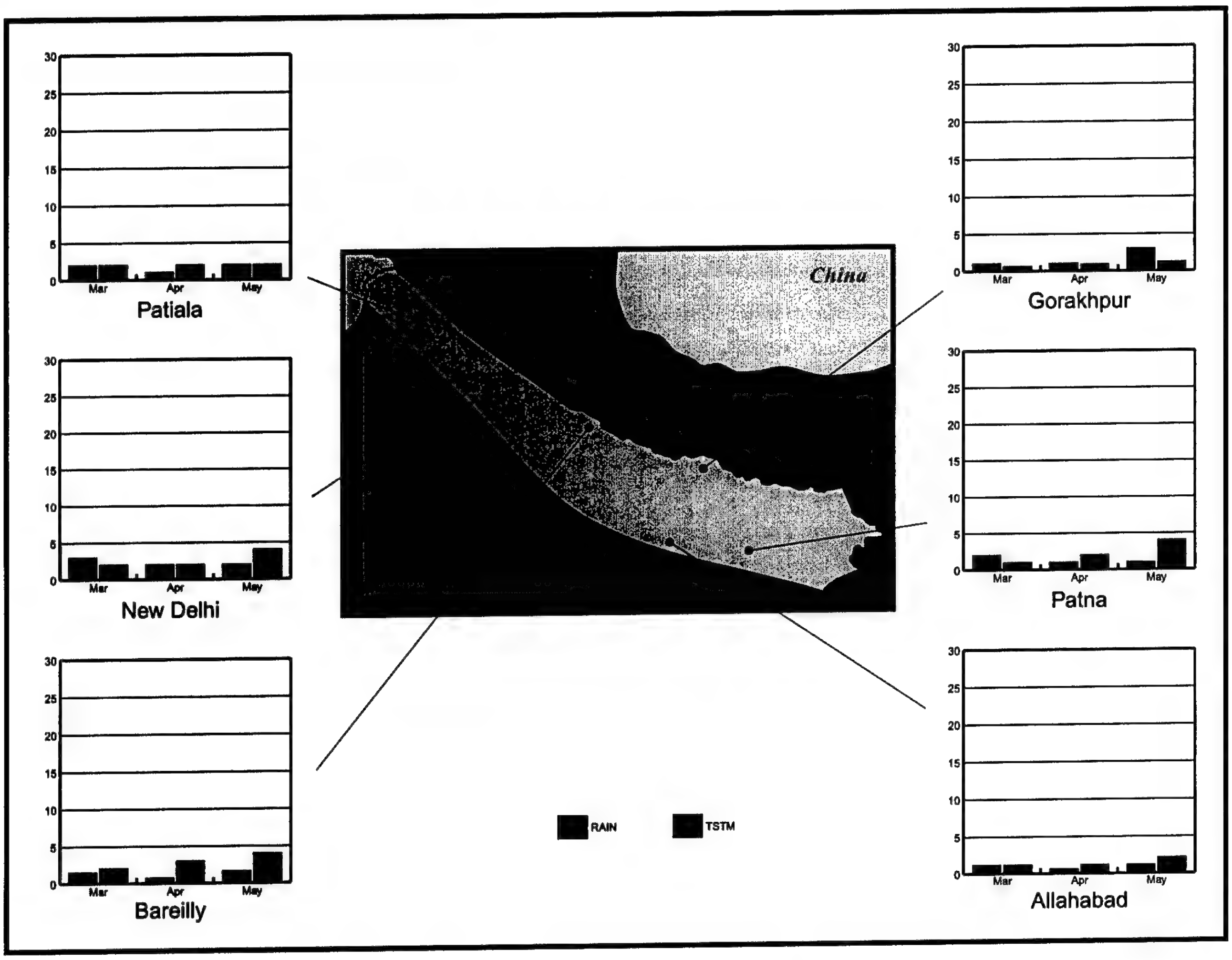


Figure 6-16. Hot Season Mean Precipitation and Thunderstorm Days. These graphs show the average seasonal occurrence of precipitation and thunderstorm days for representative locations in the region.

Temperatures. The predominantly clear skies bring the hottest temperatures of the year. Mean high temperatures are 83° to 104°F (28° to 40°C) in the northwest, 89° to 107°F (32° to 42°C) in the central areas, and 88° to 103°F (31° to 39°C) in the southeast. Mean lows are 53° to 79°F (12° to 26°C) in the northwest, 55° to 83°F (13° to 28°C) in the central areas, and 61° to 78°F (16° to 26°C) in the southeast. The coolest month is March, and the warmest is May. All locations average over 25 days with temperatures greater than 90°F (32°C) in April and May, a significant increase from March when most locations average less than 10 days with temperatures over 90°F (32°C). The extreme temperatures reported were 119°F (48°C) and 39°F (4°C). Every location reported an extreme maximum temperature higher than 110°F (43°C) in April or May. Figures 6-17 and 6-18 depict the respective mean April highs and lows.

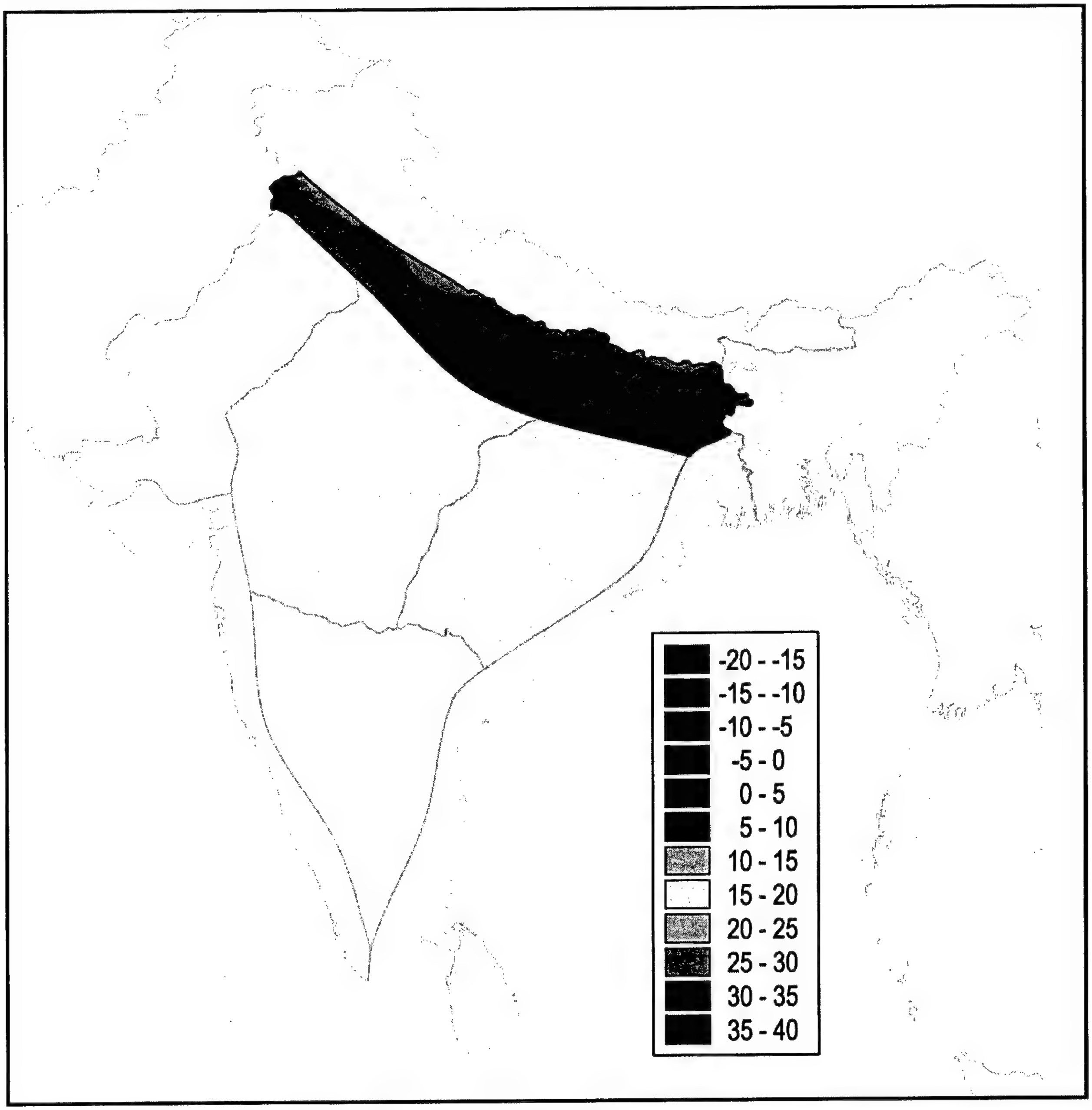


Figure 6-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

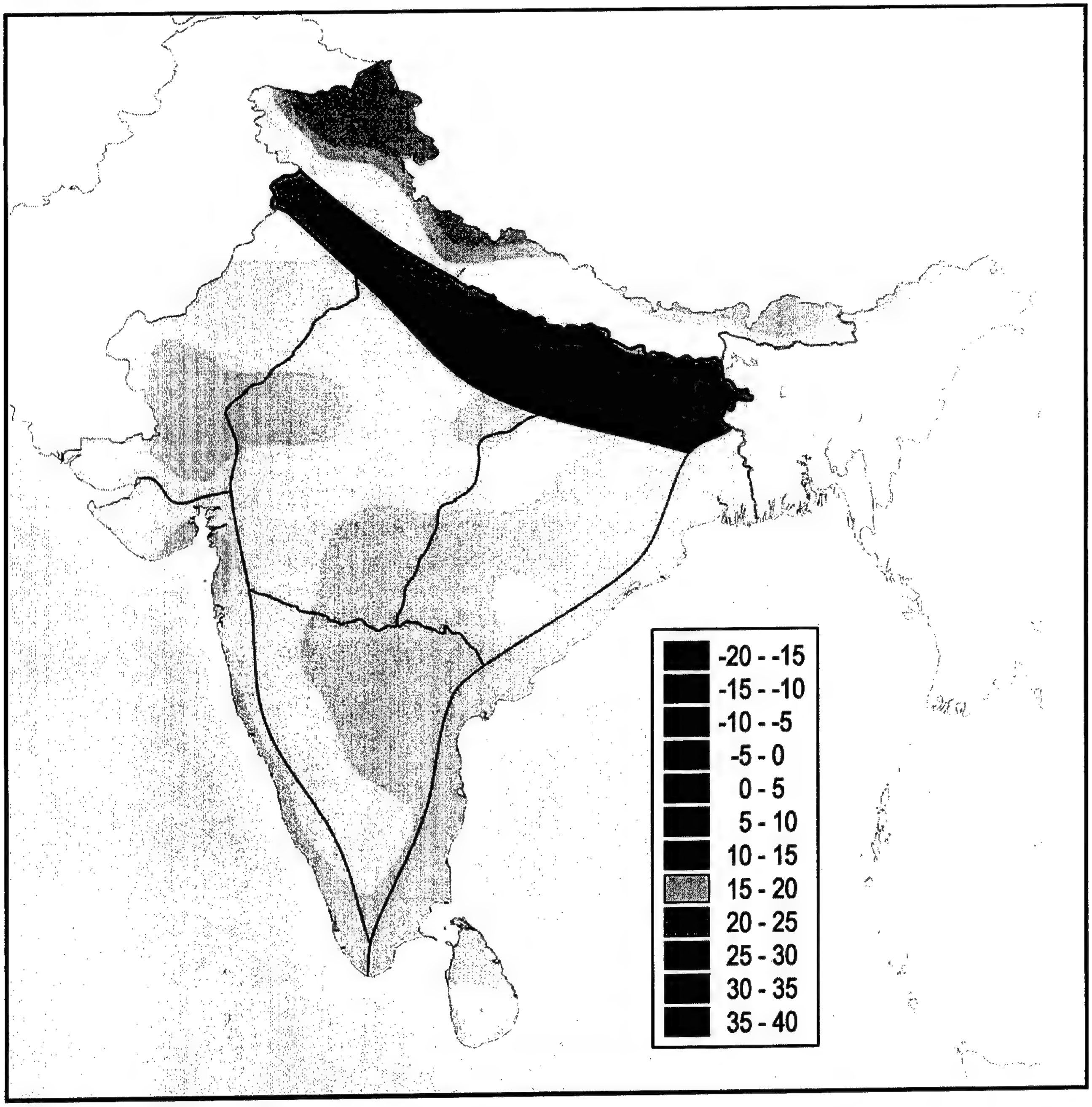


Figure 6-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. A fairly uniform pressure gradient sets up between the thermal low over northwest India and the Mascarene high in the South Indian Ocean. The Southern Hemispheric southeast trade winds cross the equator and become southwesterly. The Somali jet establishes itself while the Tibetan high moves over the plateau. The TEJ forms aloft. The southwest monsoon establishes itself over the eastern part of the region by the middle of June and is over all of it by the middle of July. The equatorial trough (ET) moves into the region and links up with the thermal low. The northwest-southeast orientation of the ET deflects the south-westerly flow of the monsoon so the low-level wind flow over the region is from the east-southeast. The ET does not remain stationary over the region. It moves north or south of its normal position and affects the orientation of the monsoonal flow. Tropical cyclone activity is rare in the north Indian Ocean when the ET lies near the base of the Himalayas. Tropical cylone activity resumes once the ET begins its southward movement in September.

The southwest monsoon season is the rainy season. Extensive cloudiness and heavy precipitation is typical; during a normal season, clear days are few. The region gets most of its annual rainfall during this season. The timing of the onset of the monsoon, as well as its intensity and duration, is critical. A late arrival, weak monsoonal flow, breaks in the monsoonal flow, or a shorter than normal season can all lead to drought. Monsoonal flow is enhanced by the development of monsoon depressions in the northern Bay of Bengal. These depressions move along the ET and sometimes travel the length of the area into Pakistan. Heavy rainfall is likely with these systems. The flow, however, is not a steady current. It undergoes a series of pulses so an active advance of rain-bearing clouds is followed by a short break in the weather before the onset of another surge of moisture. The north-south oscillation of the ET also affects regional precipitation amounts. If it moves far enough south, the region can expect a period of dry weather. If it stays south for too long, drought is likely.

Sky Cover. Cloudy skies dominate much of the region. Ceilings occur 45 percent of the time in the northwest and over 70 percent of the time in the southeast. There is a significant northwest-to-southeast increase in the occurrence of low ceilings across the region. Ceilings below 3,000 feet occur less than 10 percent of the time in the northwest, increase to 30 percent of the time in the central areas, and exceed 50 percent of the time in the southeast, as seen in Figure 6-19. The frequency of ceilings below 1,000 feet shows a similar pattern; rare in the northwest, up to 10 percent of the time in the central areas, and up to 15 percent of the time in the southeast. Low ceilings occur most in the late morning and least at night. Clouds are mostly low and middle stratiform types. Cloud formation is determined by the extension of the moist air currents and the conditions that can induce forced ascent, mainly orographic lifting and the convergence of the air current with the ET.

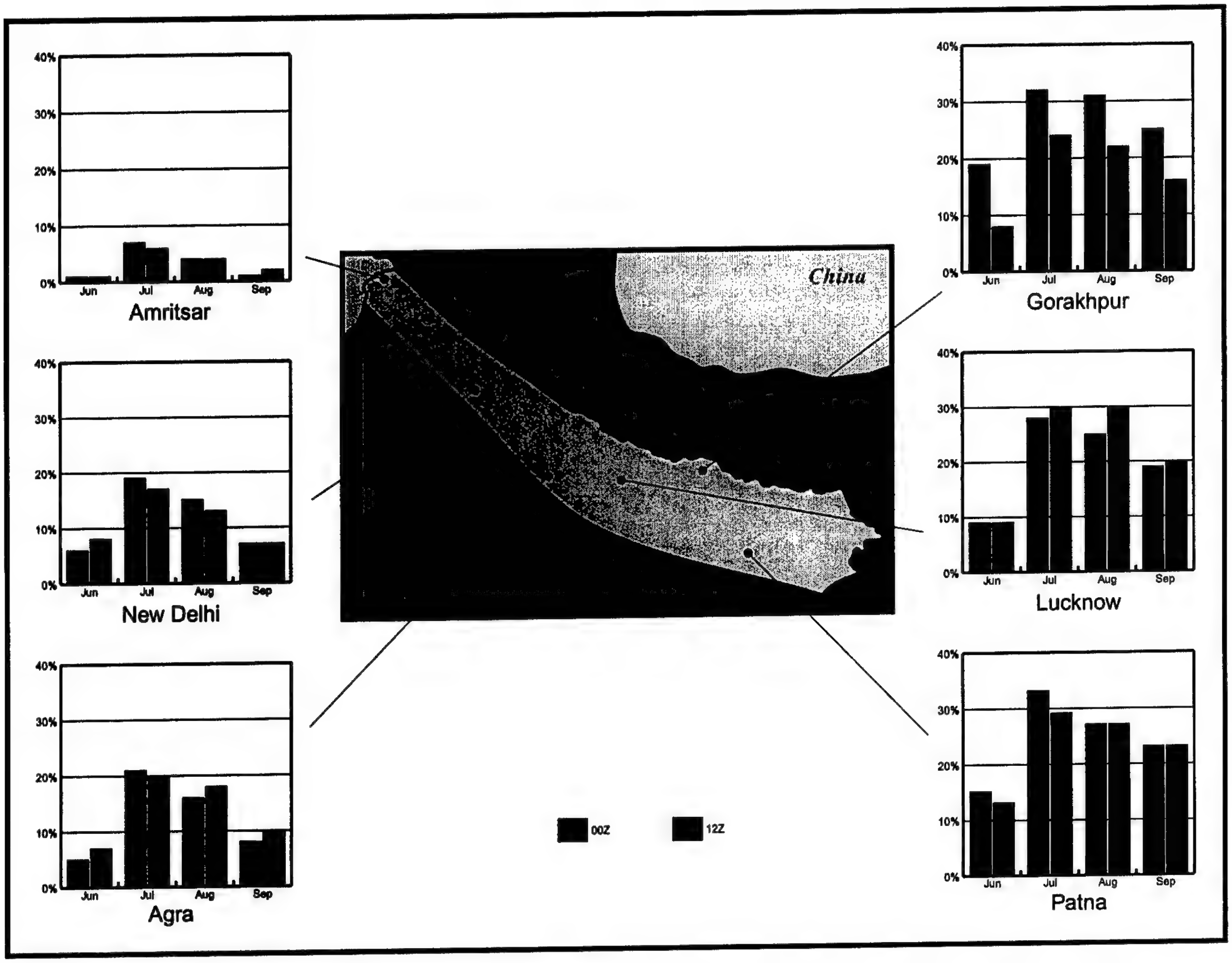


Figure 6-19. Southwest Monsoon Percent Frequency of Ceilings below 3,000 Feet. These graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location at diurnal influences.

Visibility. Visibility restrictions are less of a problem, but are still significant. Most locations report an obstruction to visibility 25-40 percent of the time. Visibility below 6 miles (9,000 meters) occurs quite often at most locations with the greatest occurrence overnight and in the early morning hours. Except for June in the central and northwestern parts of the region, visibility below 2 1/2 miles (4,000 meters) generally occurs less than 20 percent of the time (see Figure 6-20). The northwestern and central areas are plagued by blowing dust and sand in June and have significant visibility restrictions over 60 percent of the time.

Visibility below 1 1/4 miles (2,000 meters) occurs less than 10 percent of the time, with the highest incidence in June. With the onset of the monsoon rains, precipitation replaces haze and smoke as the biggest factor for reduced visibility for many locations. Blowing dust and sand are not much of a factor once the rains moisten the ground. If an extended monsoon break occurs and drought sets in, blowing dust and sand will become significant again. Morning fog presents a problem around rivers.

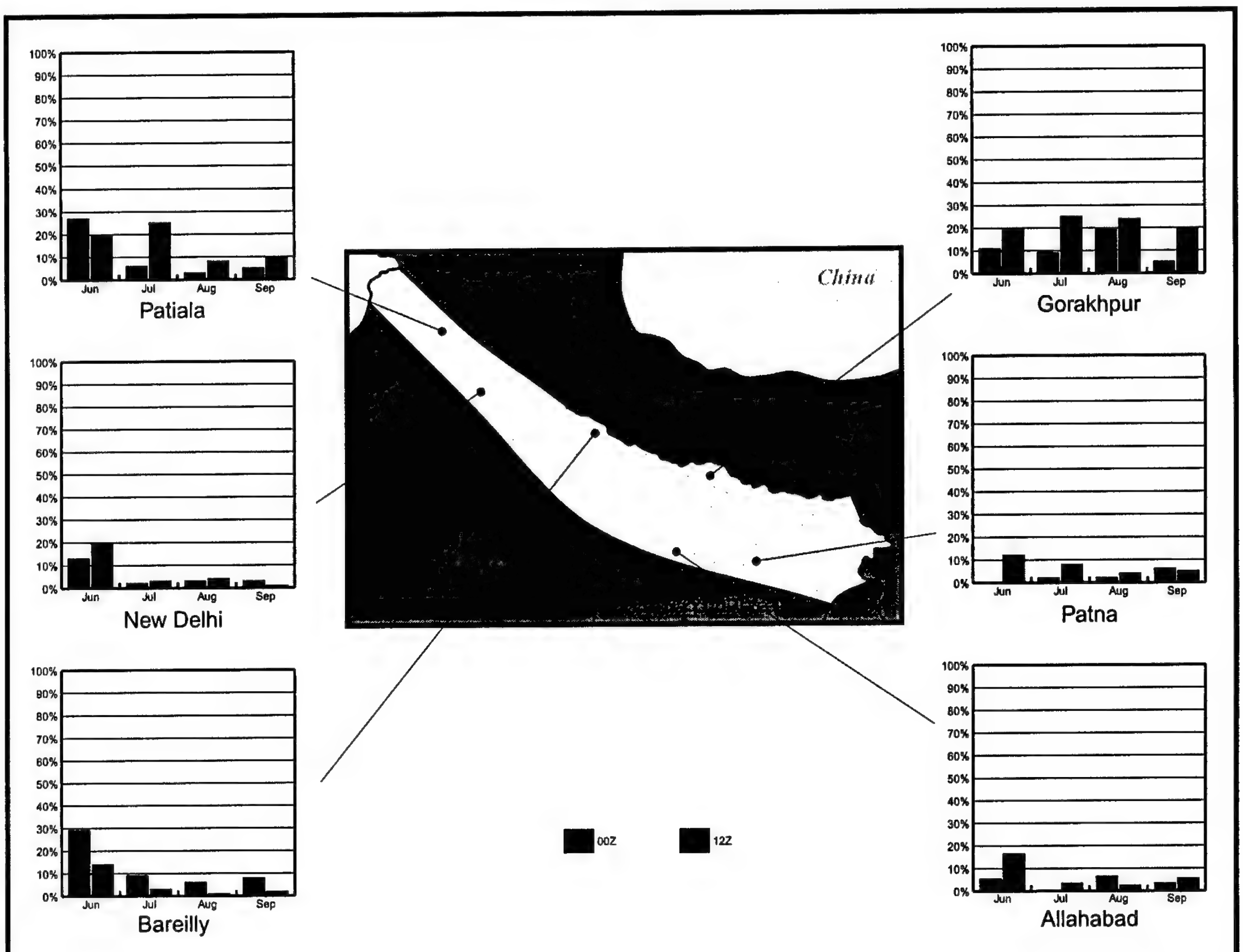


Figure 6-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). These graphs show a monthly breakdown of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. East to southeast winds prevail as the ET positions itself over the region (see Figure 6-21). Since the ET is not fully in place until July, the western half of the region still has northwesterly winds in June. Northwesterly winds return to the western half of the region in September as the ET withdraws. Average speeds are 5-10 knots. Thunderstorm gusts to 90 knots have been reported. Since the ET is not static, the prevailing wind direction will change as the ET oscillates north and south. Also, locations along the southern border of the region, especially adjacent to the Thar Desert, can have winds from the south or southwest if the southwesterly wind flow from the Arabian Sea is strong enough to reach the Indo-Gangetic Plain.

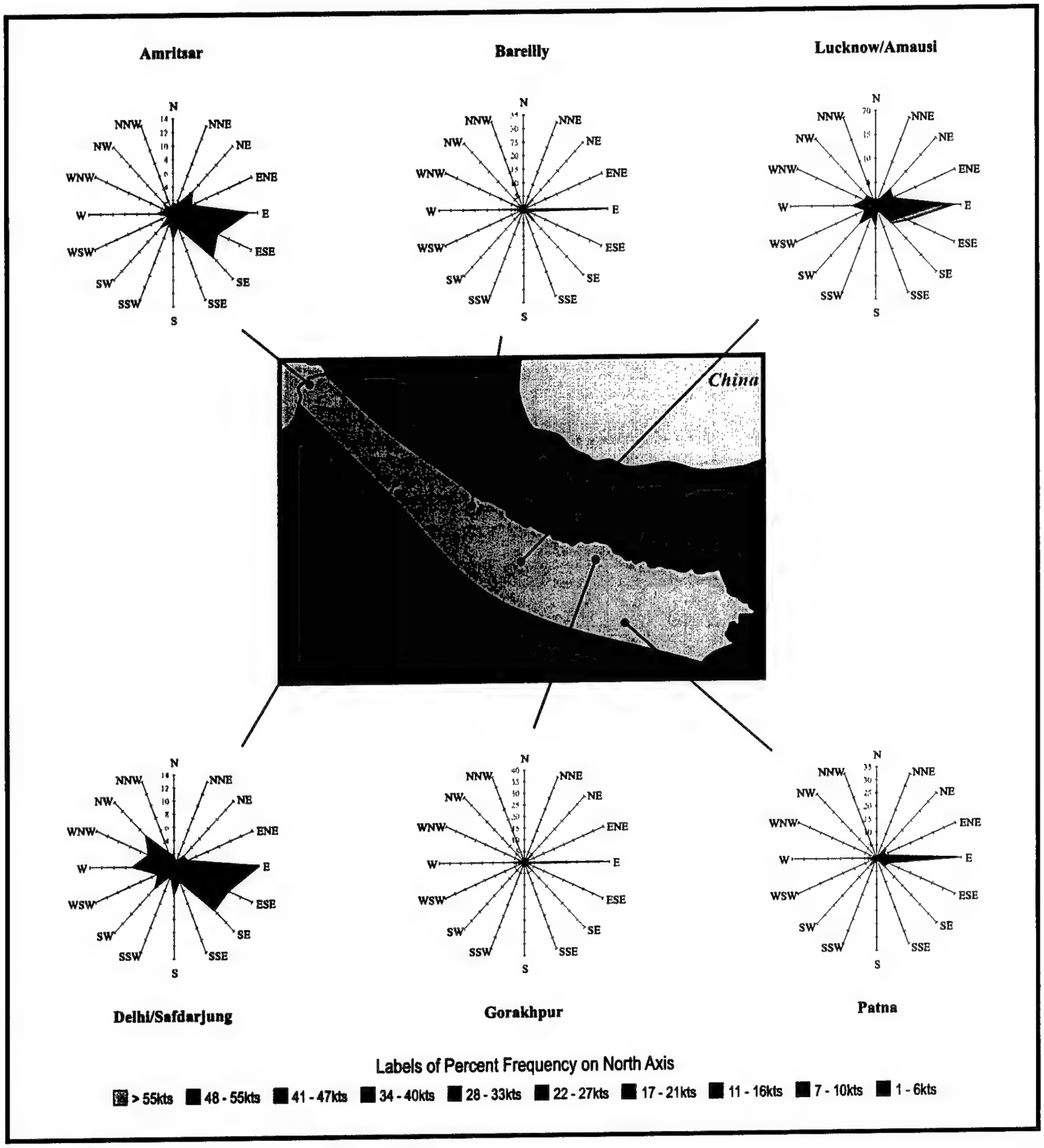


Figure 6-21. July Surface Wind Roses. The figures shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. The upper-air wind pattern undergoes two complete reversals in direction. West to northwest winds are present from the surface to 200 mb in June with 5-10 knot wind speeds. The wind shifts around to the east above 200 mb due to the Tibetan high's movement over the region. Westerly winds are still present in July through the 500-mb level, above which the winds shift to the east. The 850-mb wind rose for Lucknow indicates the occasional presence of the monsoon flow off the Bay of Bengal. Wind speeds are less than 20 knots through 150 mb. They increase to 40 knots above 100 mb due to the development of the tropical easterly jet south of the region. Speeds average 10-20 knots up to 200 mb, then increase above that level to 40 knots. Westerly winds reappear below 300 mb in September as the southwest monsoon begins its withdrawal. Easterly winds remain above 300 mb. Wind speeds are below 25 knots at all levels. Figure 6-22 is a composite showing the upper-level winds for July over New Delhi and Lucknow.

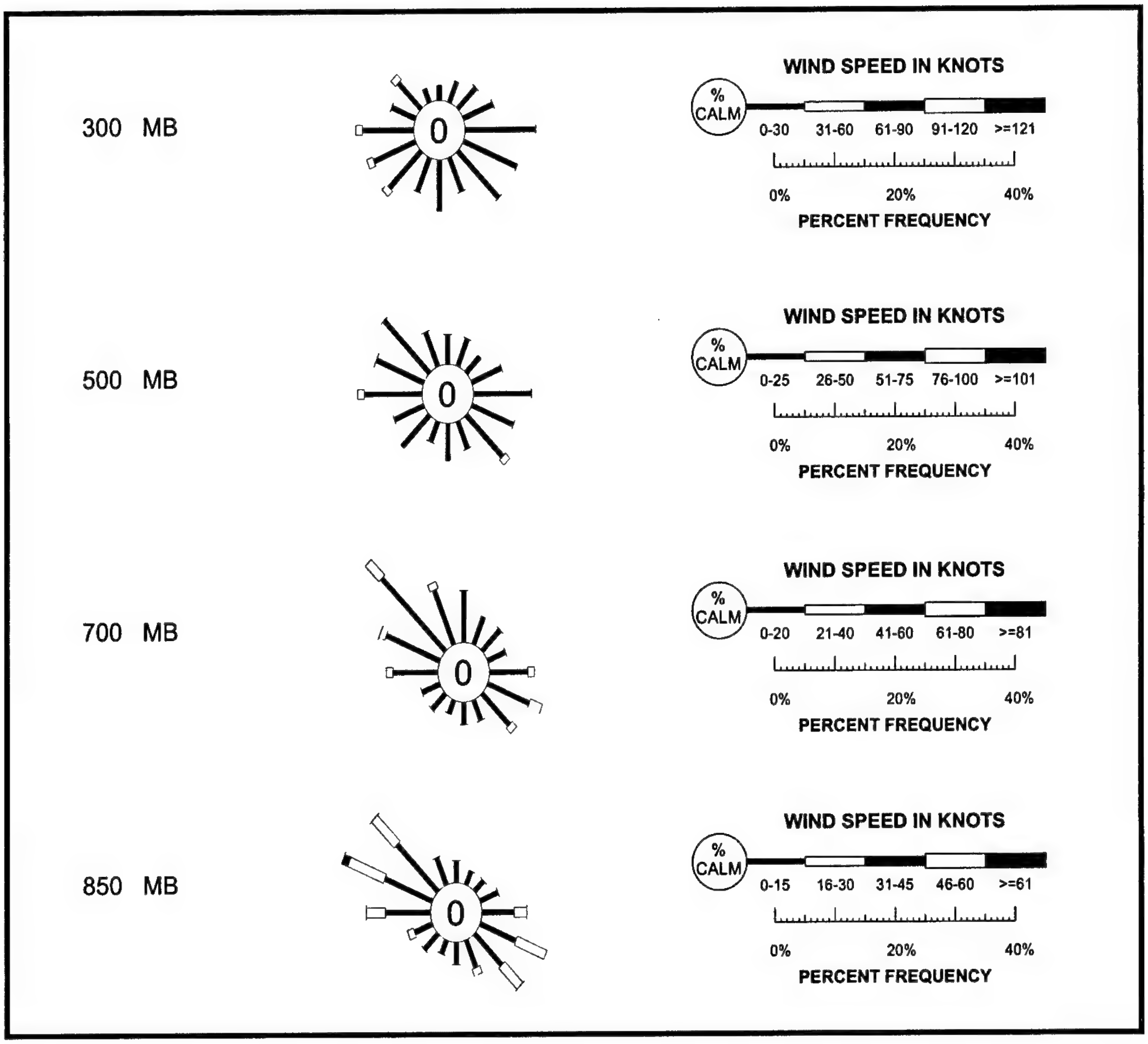


Figure 6-22. July Upper-Air Wind Roses. The composite wind roses depict speed and direction for standard pressure surfaces between 850 and 300 mb at New Delhi and Lucknow.

Precipitation. June through September is the rainy season. The area receives 75-90 percent of its annual rainfall during this period. Seasonal rainfall amounts range from nearly 14 inches (356 mm) in the northwest to nearly 46 inches (1,168 mm) in the southeast. Sites along the Himalayas have the highest amounts due to orographic lifting. Monthly totals range from 1.5-10 inches (38-254 mm) in the northwest to 4-14 inches (102-356 mm) in the southeast (see Figure 6-23). Maximum monthly rainfall amounts up to 40 inches (1,016 mm) have been reported. June is the driest month; July and August are the wettest. Rain is not an everyday

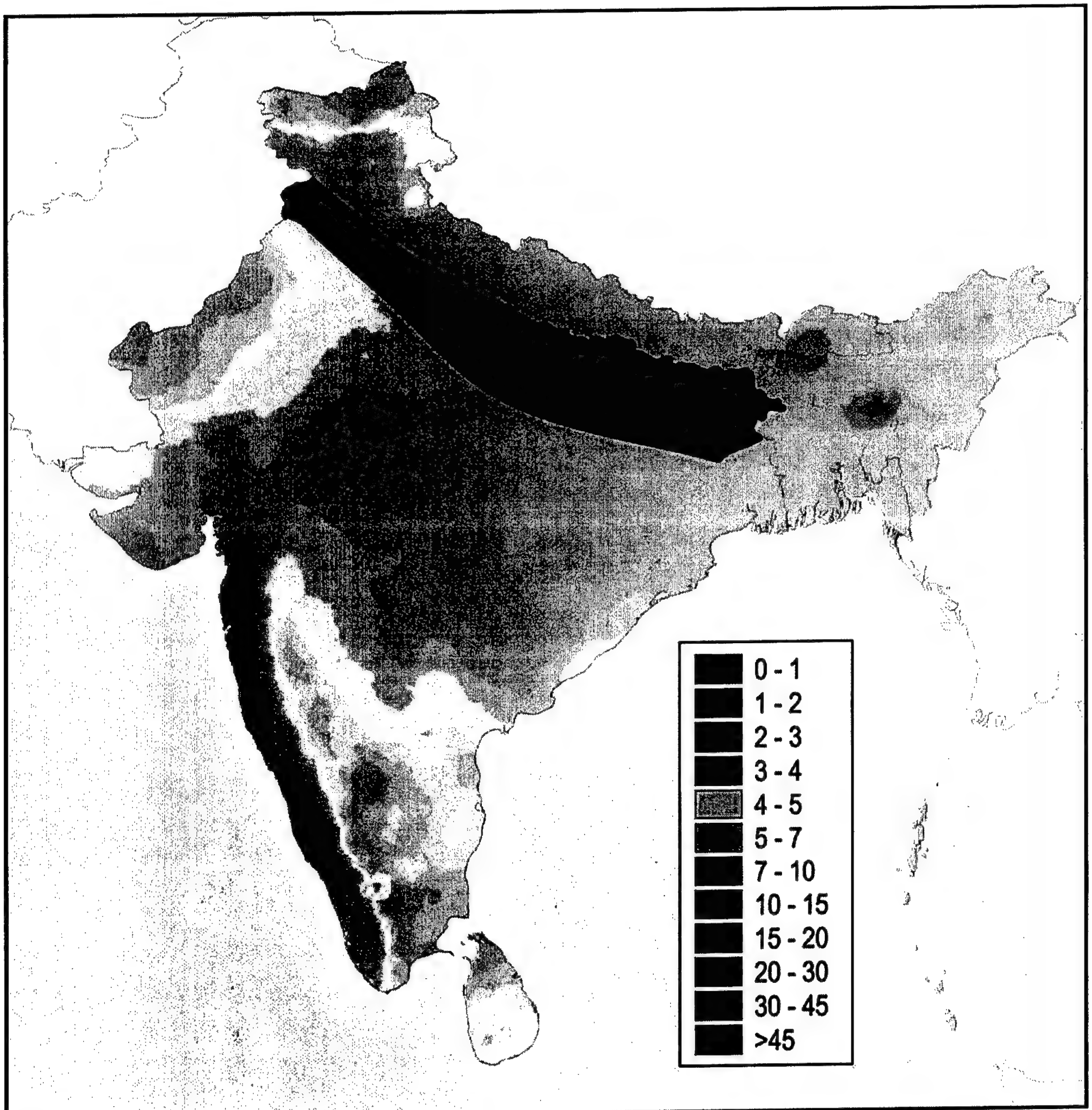


Figure 6-23. July Mean Precipitation (Inches). These graphs depict the mean amount of precipitation received for representative locations in the region.

occurrence. It is observed 4-10 days per month over the western half of the area and up to 15 days per month over the eastern half. Thunderstorm activity increases; most locations can expect 4-8 thunderstorm days per month (see Figure 6-24). Monsoon depressions provide most of the rain. The depressions cause 2-3 days of heavy rain at a time.

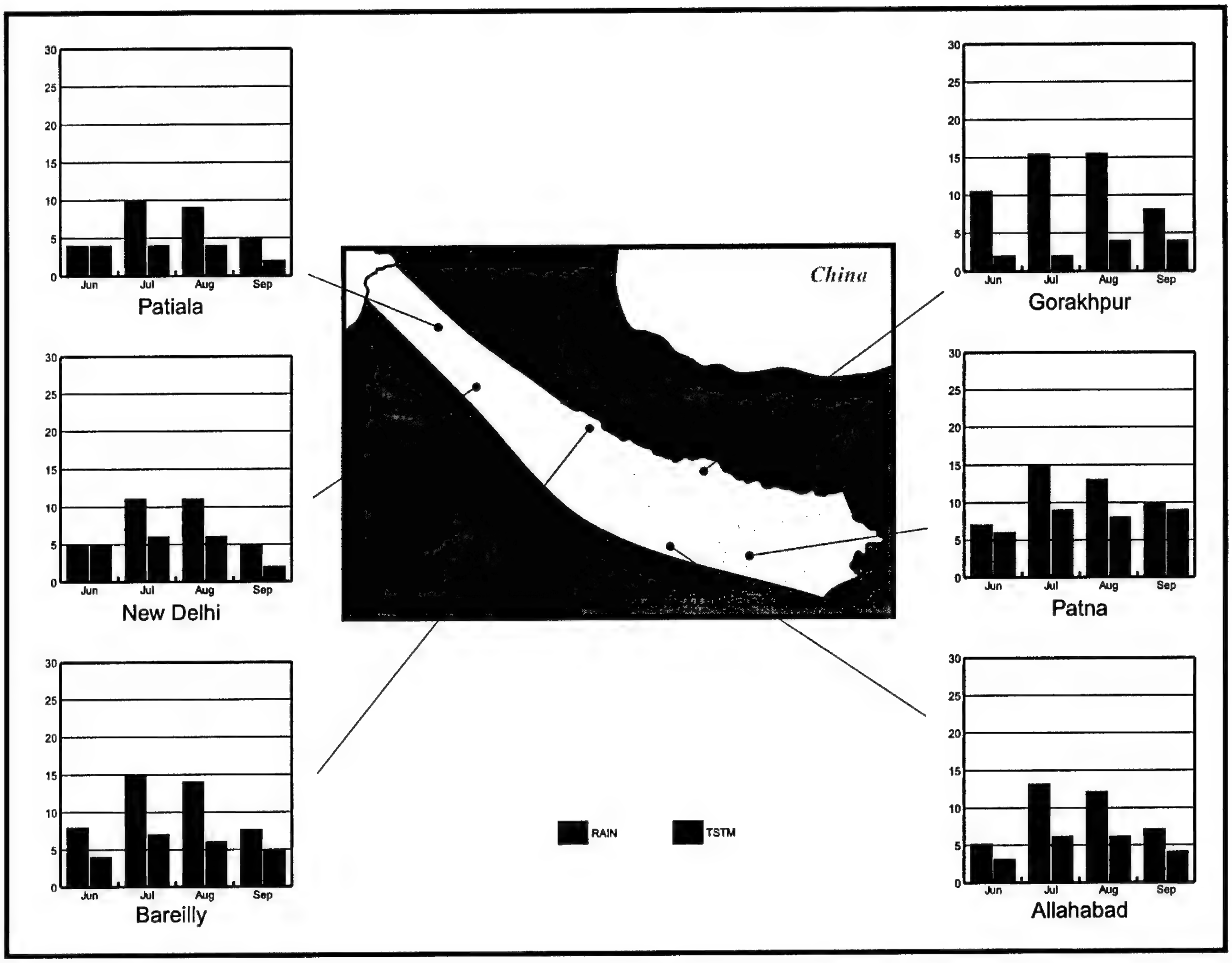


Figure 6-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. These graphs show the average seasonal occurrence of precipitation and thunderstorm days for representative locations in the region.

Temperatures. The onset of the extensive cloud cover and the southwest monsoon rains bring some relief from the high temperatures of the hot season. June is the hottest month with a mean high near 95°F (35°C) in the southeast and near 105°F (41°C) in the northwest (see Figure 6-25). Mean lows in June are 80° to 85°F (27° to 29°C) across the entire area. The temperatures for the remainder of the season show a monthly decrease with the mean highs down to 90° to 95°F (32° to 35°C). The mean lows cool to 75° to 80°F (24° to 27°C), as shown in Figure 6-26. The extremes reported were 119°F (48°C) and 55°F (13°C).

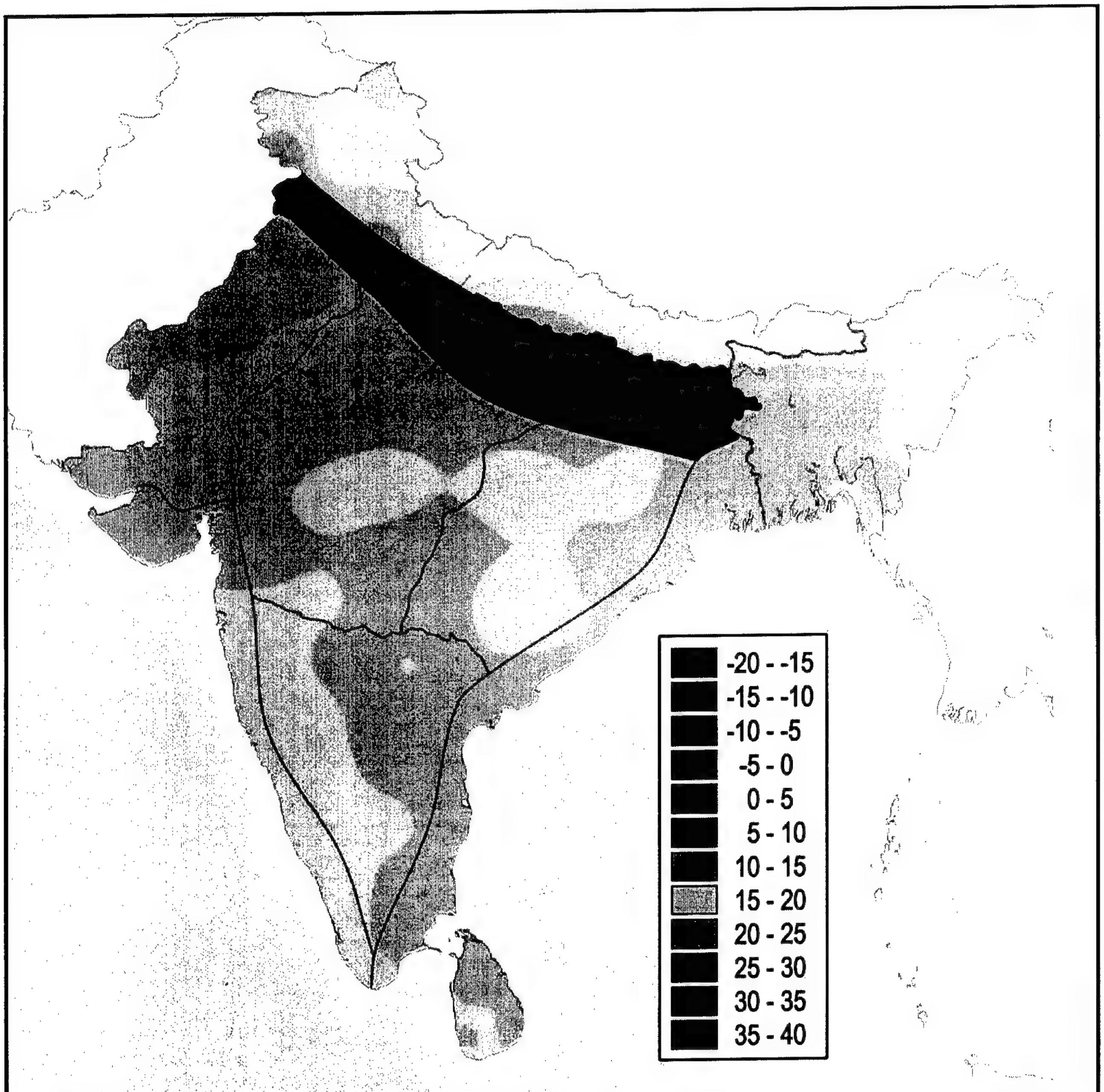


Figure 6-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

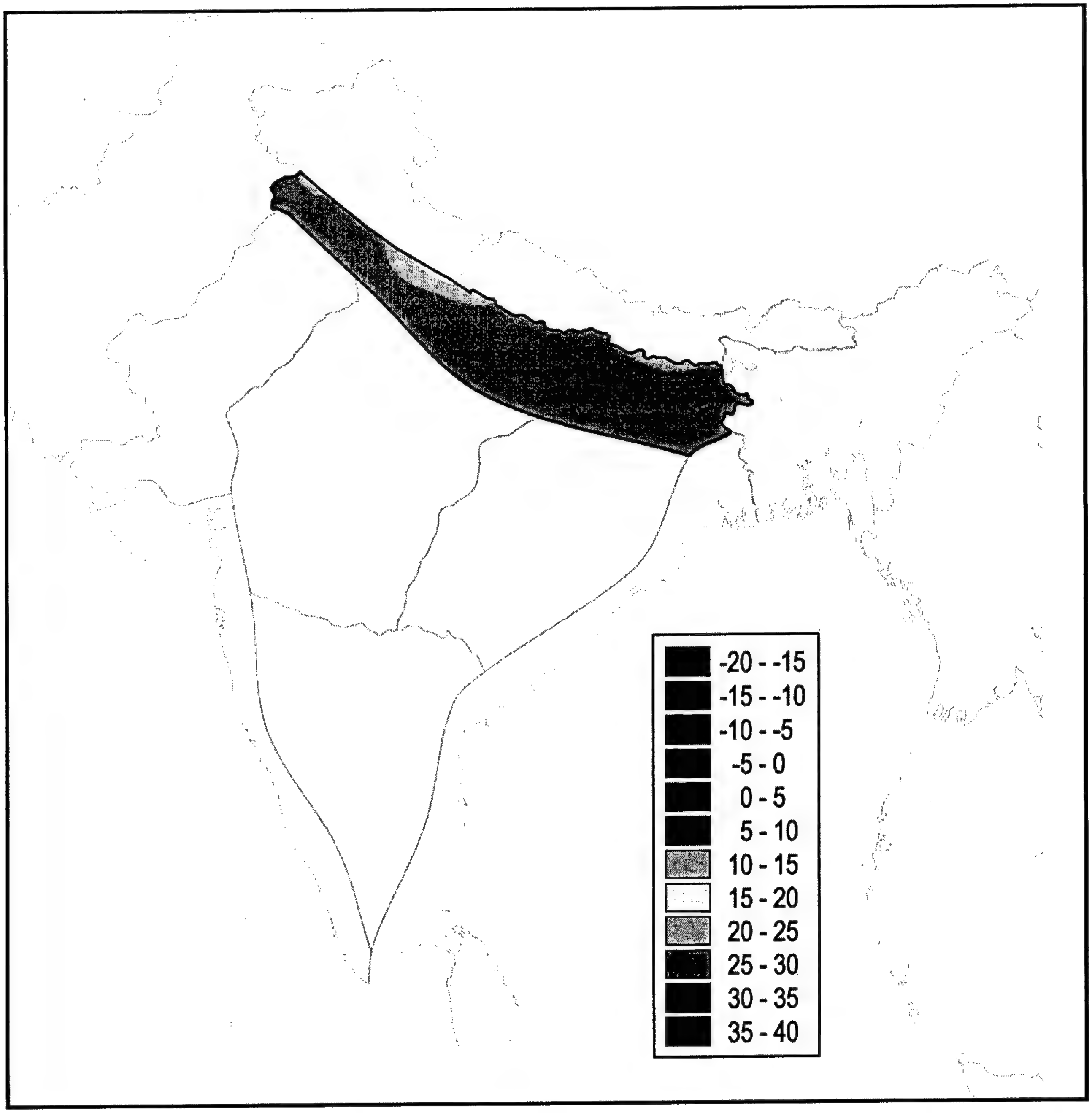


Figure 6-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. This season transitions to the northeast monsoon. The equatorial trough (ET) moves south and will normally clear the region by the middle of October. The Asiatic low weakens and is replaced by the Asiatic high. The TEJ, the equatorial westerlies, and the Somali jet all disappear. The circulation pattern approaches that of the winter season. Tropical cyclone activity increases as the ET moves towards the equator.

The weather depends on the air mass present. The southwest monsoon may reappear in early October to bring clouds and heavy precipitation. When the southwest monsoon has completely retreated, the surge of high pressure may cause hot season weather. Dry weather with high daytime, but fairly low nighttime temperatures, good-to-excellent visibility, and light-to-moderate surface winds are prevalent. As the season progresses into November, polar continental air moves in from the northwest with clear skies, low humidity and large diurnal temperature ranges. The winds are generally light out of the north or northwest. Western disturbances will move through the region after the Himalayan lee-side trough sets up by the end of November or early in December.

Sky Cover. There is a rapid decrease in cloudiness behind the southwest monsoon. Clear to scattered skies are the rule. Any ceilings occur less than 10 percent of the time in the northwest and 15-20 percent of the time in the southeast. Ceilings below 3,000 feet generally occur less than 10 percent of the time in the northwest and 15 percent of the time in the southeast in October (see Figure 6-27). In November, ceilings below 3,000 feet occur less than 5 percent of the time for the entire area. Ceilings below 1,000 feet rarely occur. The most low ceilings occur in late morning and early afternoon. Cloud types in early October are similar to those of the southwest monsoon. Once the southwest monsoon has left the area, middle and high type clouds prevail, usually altocumulus and cirrus. Low stratus develops in the early morning hours over the river valleys and dissipate after sunrise.

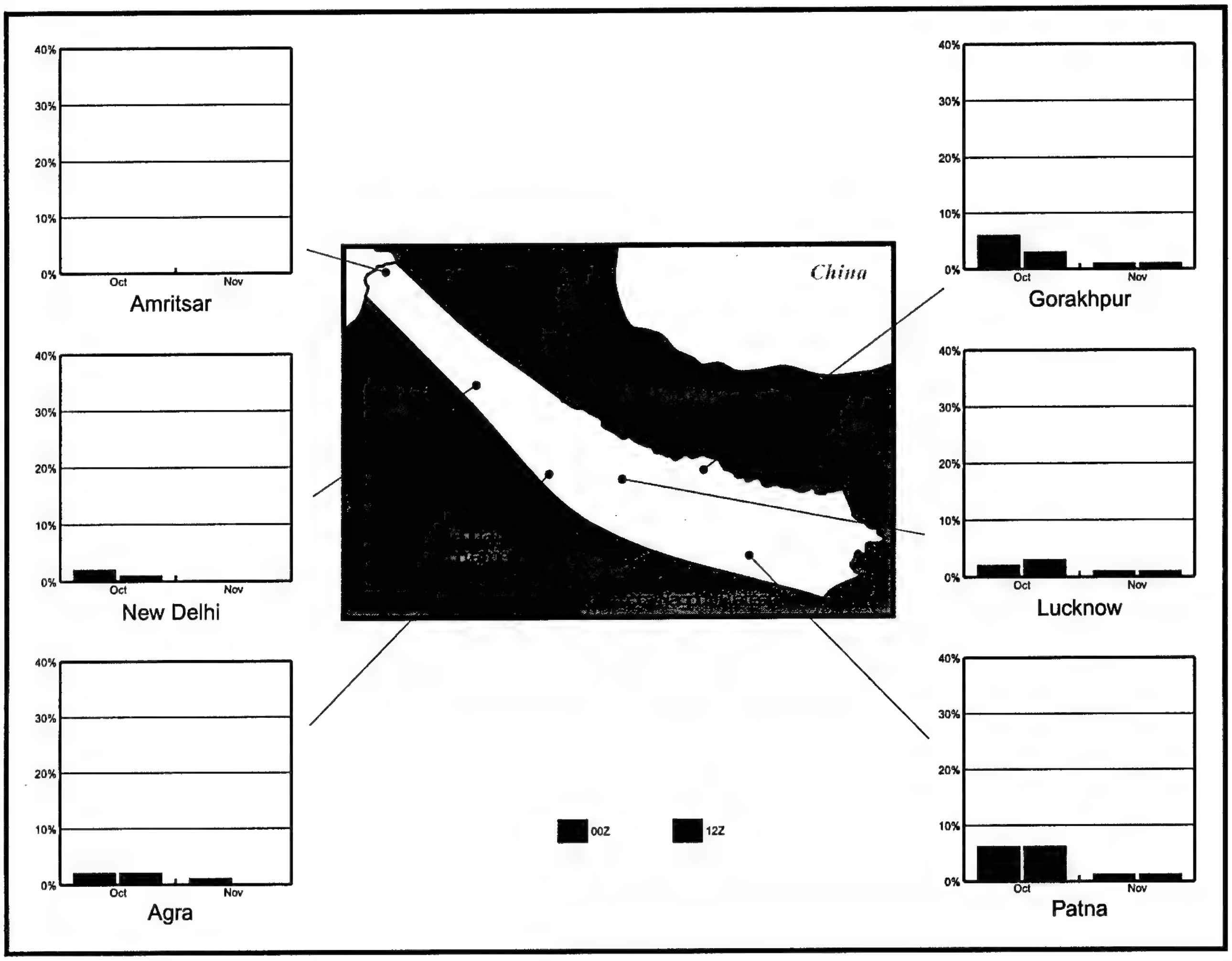


Figure 6-27. Post Monsoon Percent Frequency of Ceilings below 3,000 Feet. These graphs show a monthly breakdown of the percent of ceilings below 3,000 feet based on location and diurnal influences.

Visibility. Visibility problems increase. Many locations report an obstruction to visibility in up to 85 percent of the observations taken. Visibility below 6 miles (9,000 meters) occurs quite often at most locations. Visibility below 2 1/2 miles (4,000 meters) generally occurs less than 20 percent of the time, but a few exceed 30 percent of the time (see Figure 6-28). Visibility below 1 1/4 miles (2,000 meters) occurs less than 10 percent of the time, usually in the morning. Haze and smoke are the biggest factors, followed by fog and precipitation. Blowing dust and sand present a slight problem for some locations in the northwest, and morning fog affects sites around rivers.

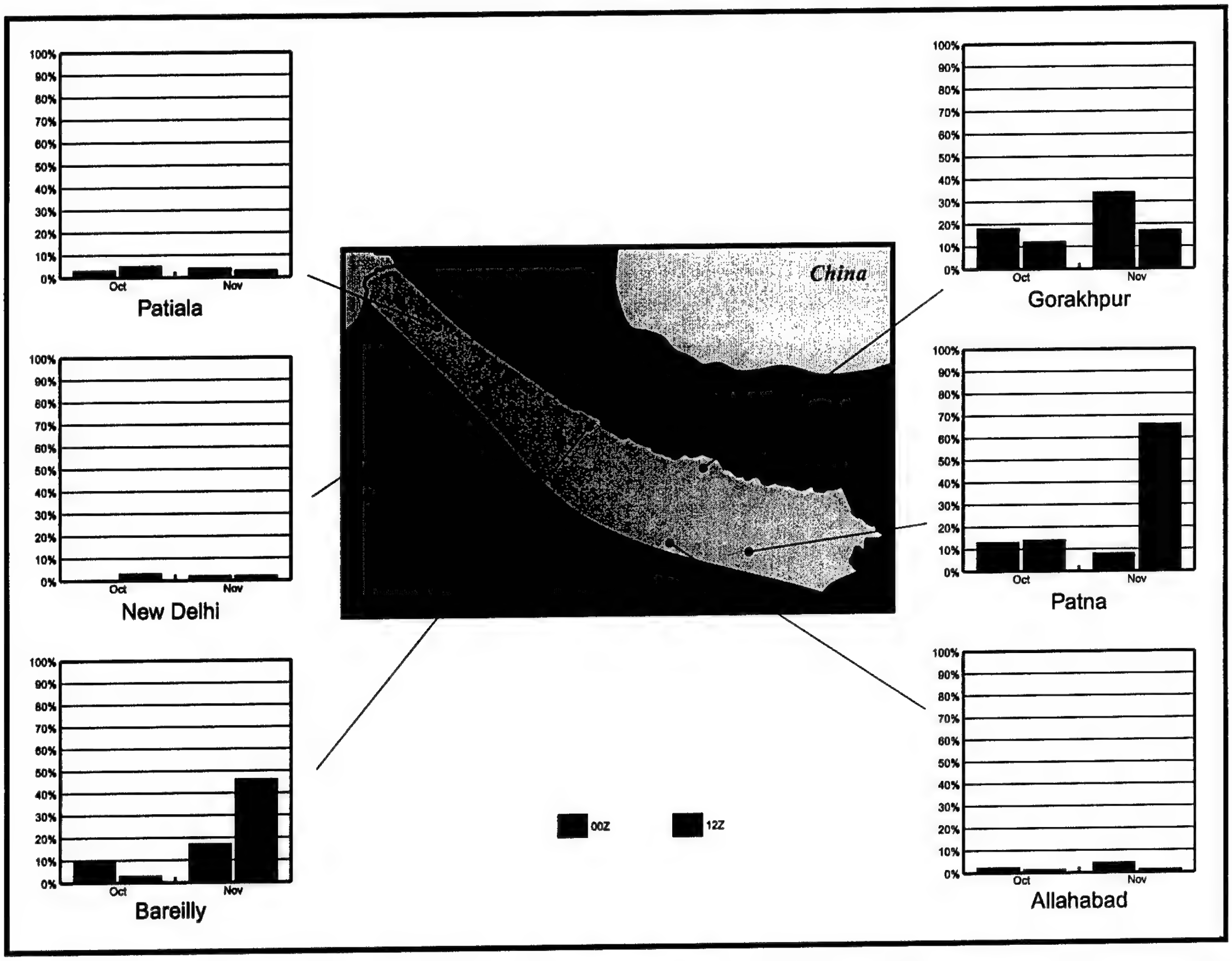


Figure 6-28. Post Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). These graphs show a monthly breakdown of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. West to northwest winds return to the western half of the region in October, and cover the entire region by late October, as seen in Figure 6-29. Easterly winds dominate the eastern part of region in the first half of October until the southwest monsoon has left the area. Average speeds are 3-6 knots. Thunderstorm gusts up to 40 knots have been reported.

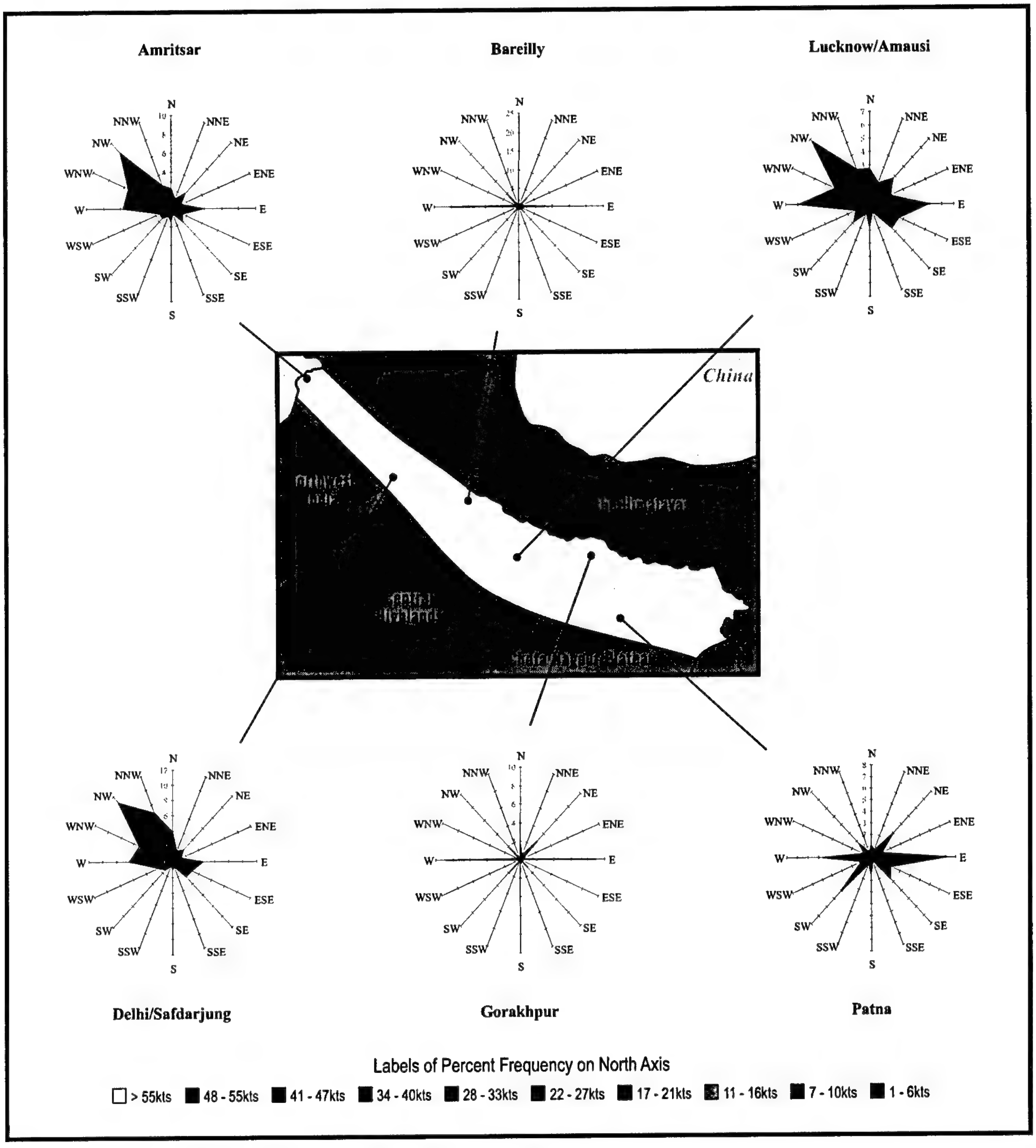


Figure 6-29. October Surface Wind Roses. The figures shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Air Winds. West to northwest winds are present from the surface to 50,000 feet behind the southwestern monsoon. Winds average 5-15 knots in the first 15,000 feet, then increase as the STJ returns south of the Himalayas in November. Wind speeds increase steadily and peak at 65-75 knots at 39,000 feet, the level of the STJ. They begin to diminish above 40,000 feet. Figure 6-30 is a composite showing the upper-level winds for October at New Delhi and Lucknow.

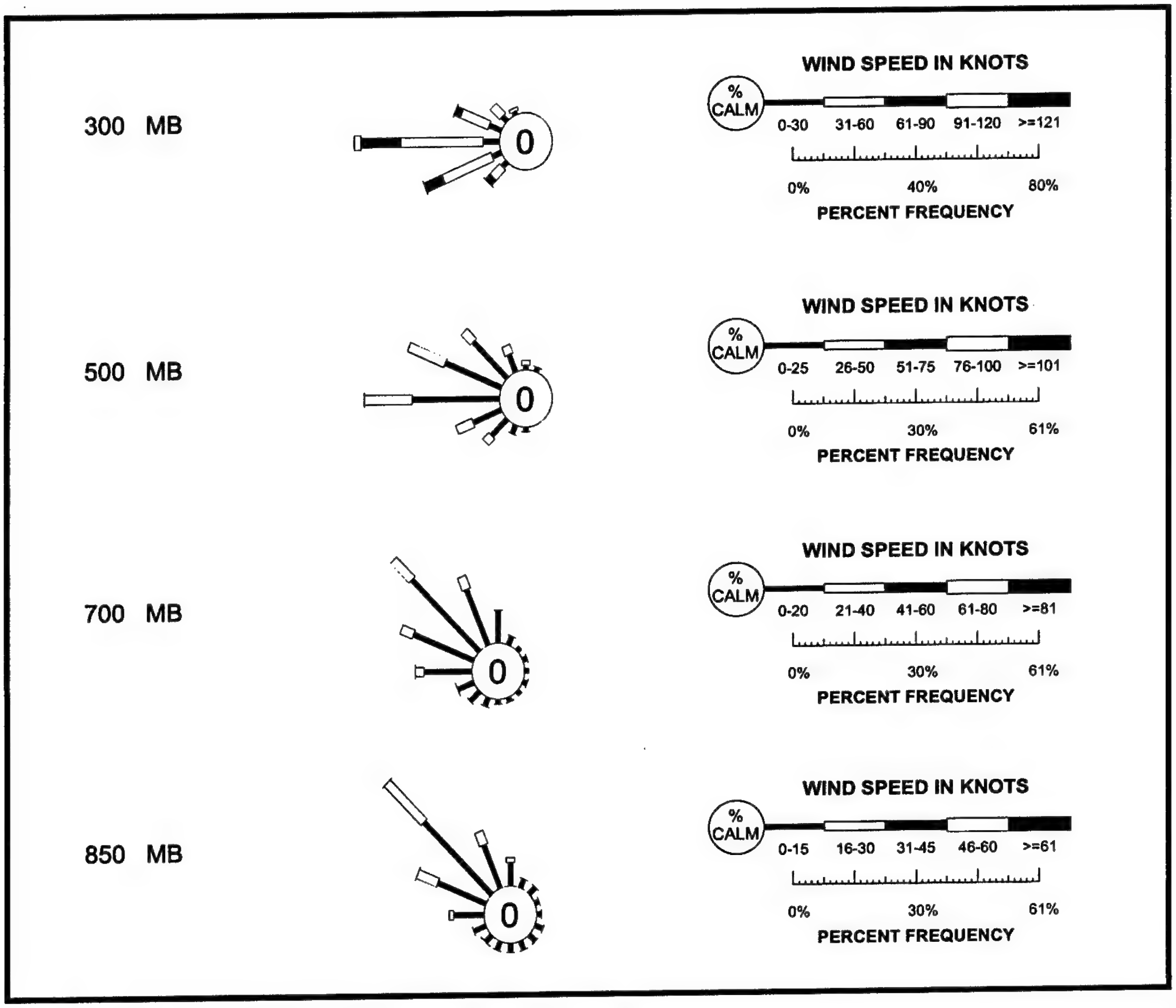


Figure 6-30. October Upper-Air Wind Roses. The wind roses depict speed and direction for standard pressure surfaces between 850 and 300 mb at New Delhi and Lucknow.

Precipitation. Rainfall drops off dramatically after the southwest monsoon. Many locations receive less rain in the post-monsoon season than during the hot season. More rain falls in October than November, especially in the eastern part of the region, which continues to get rainfall from the southwest monsoon through the middle of the month (see Figure 6-31). Seasonal amounts range from less than .5 inch (15 mm) in the west to over 3 inches (76 mm) in the east. Monthly totals range from less than .25 inch (6 mm) in the west to under 3 inches (76 mm) in the east. The extreme monthly rainfall reported (October) ranged from 3.5 inches (89 mm) in the west to over 20 inches (508 mm) in the east. In October, thunderstorms are responsible for most of the rainfall in the west, while the retreating southwest monsoon provides most of the rain in the east. In November, western disturbances are responsible for much of the rainfall. The number of rain days also decreases significantly. Most of the locations have less than 4 days with rain in October, and 2 or less in November (see Figure 6-32). Thunderstorm activity also decreases to 2 days or less each month. Some of the thunderstorms provide little or no rain, especially in the western part of the region.

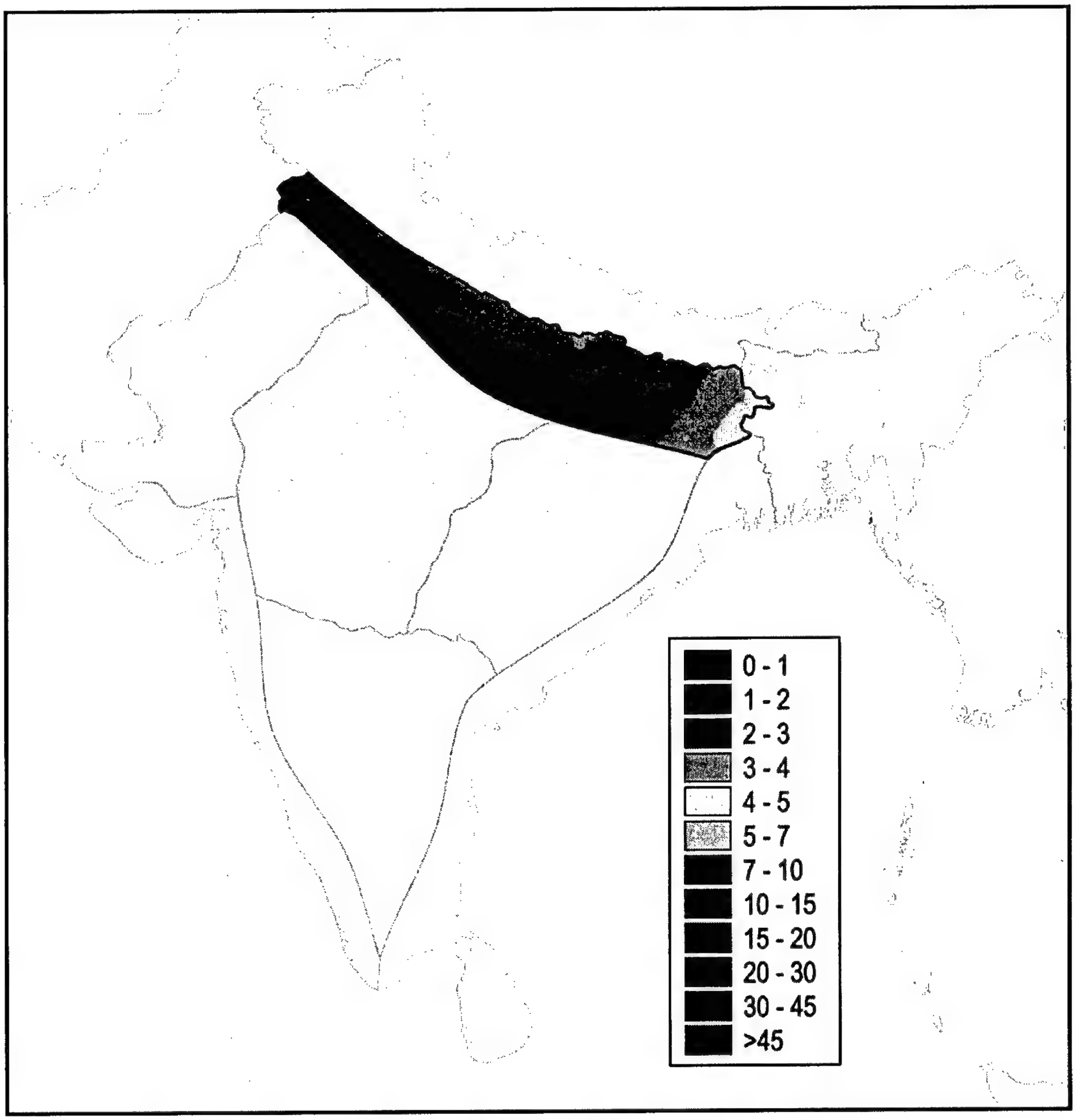


Figure 6-31. Post-Monsoon Mean Precipitation (Inches). These graphs depict the mean amount of precipitation received for representative locations in the region.

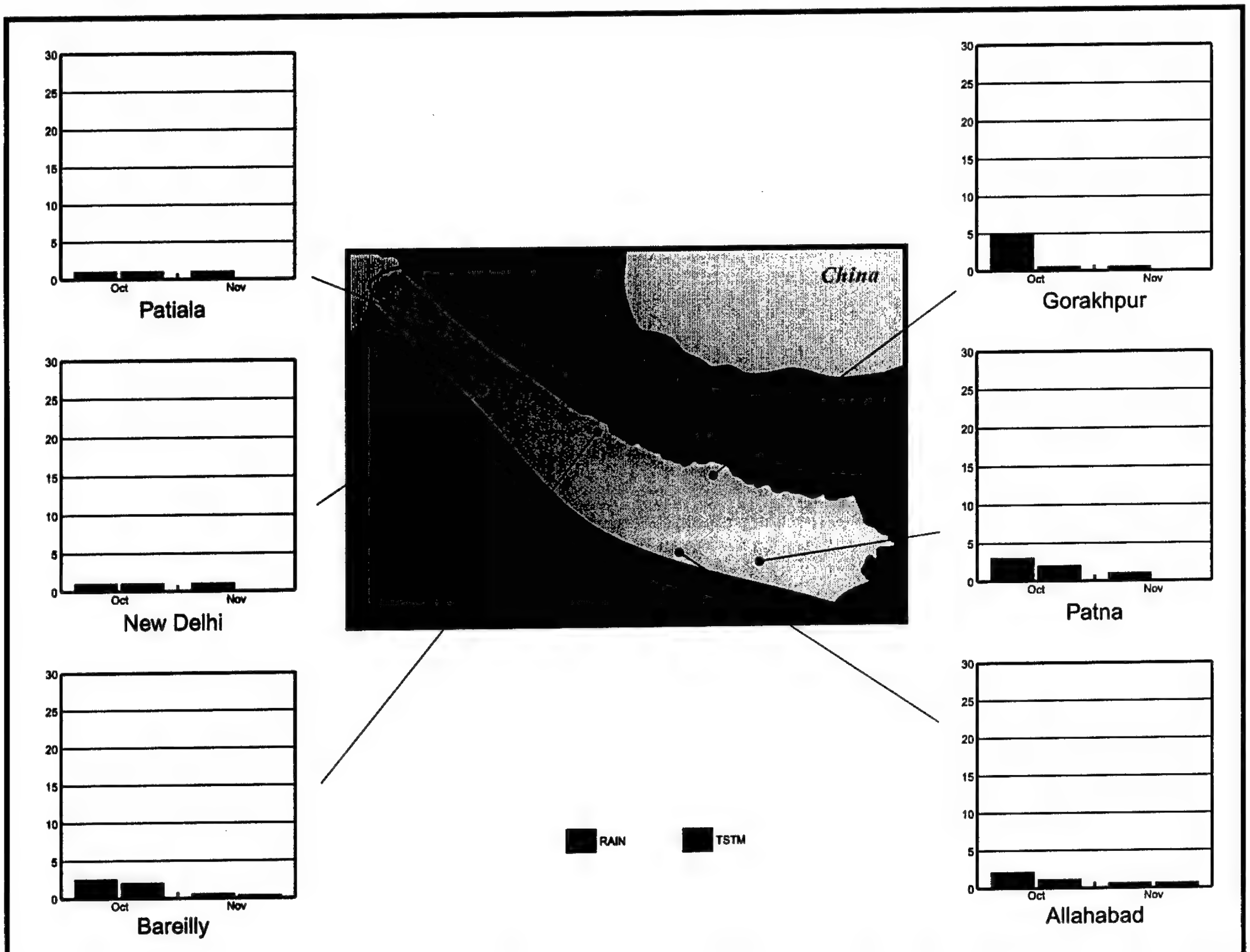


Figure 6-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. These graphs show the average seasonal occurrence of precipitation and thunderstorm days for representative locations in the region.

Temperatures. A temporary increase in temperatures takes place right after the retreat of the southwest monsoon, then temperatures decrease. Mean highs in October are 88°F (31°C) in the southeast and 94°F (34°C) in the northwest. Mean lows are 60°F (15°C) in the northwest and 73°F (23°C) in the southeast. In November, the mean high is 80° to 85°F (27° to 29°C) across the region. The mean lows have greater variability, from near 50°F (10°C) in the northwest to near 60°F (15°C) in the southeast. The extreme temperatures reported were 110°F (43°C) and 35°F (2°C). See Figures 6-33 and 6-34 for respective mean regional highs and lows in October.

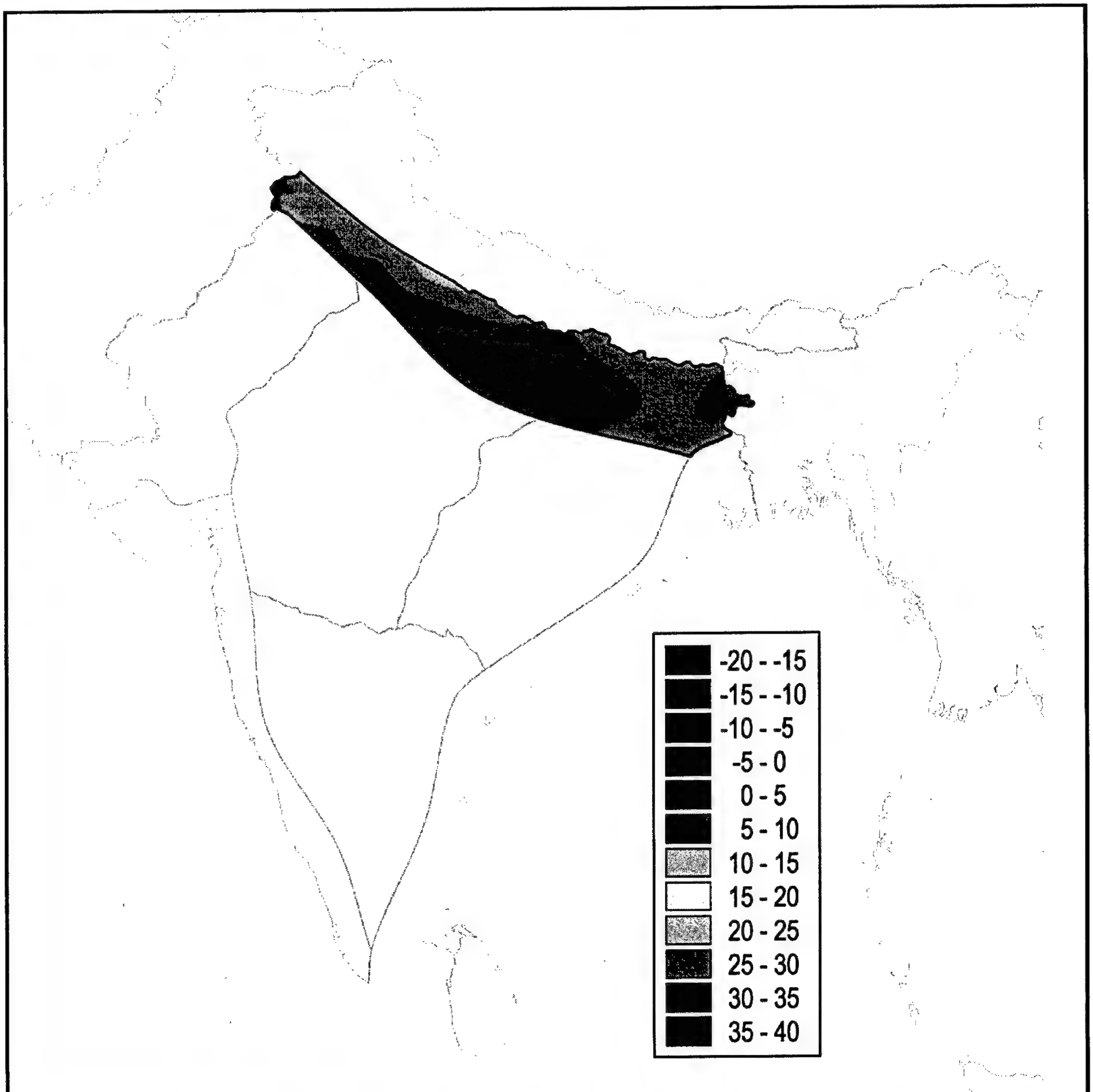


Figure 6-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

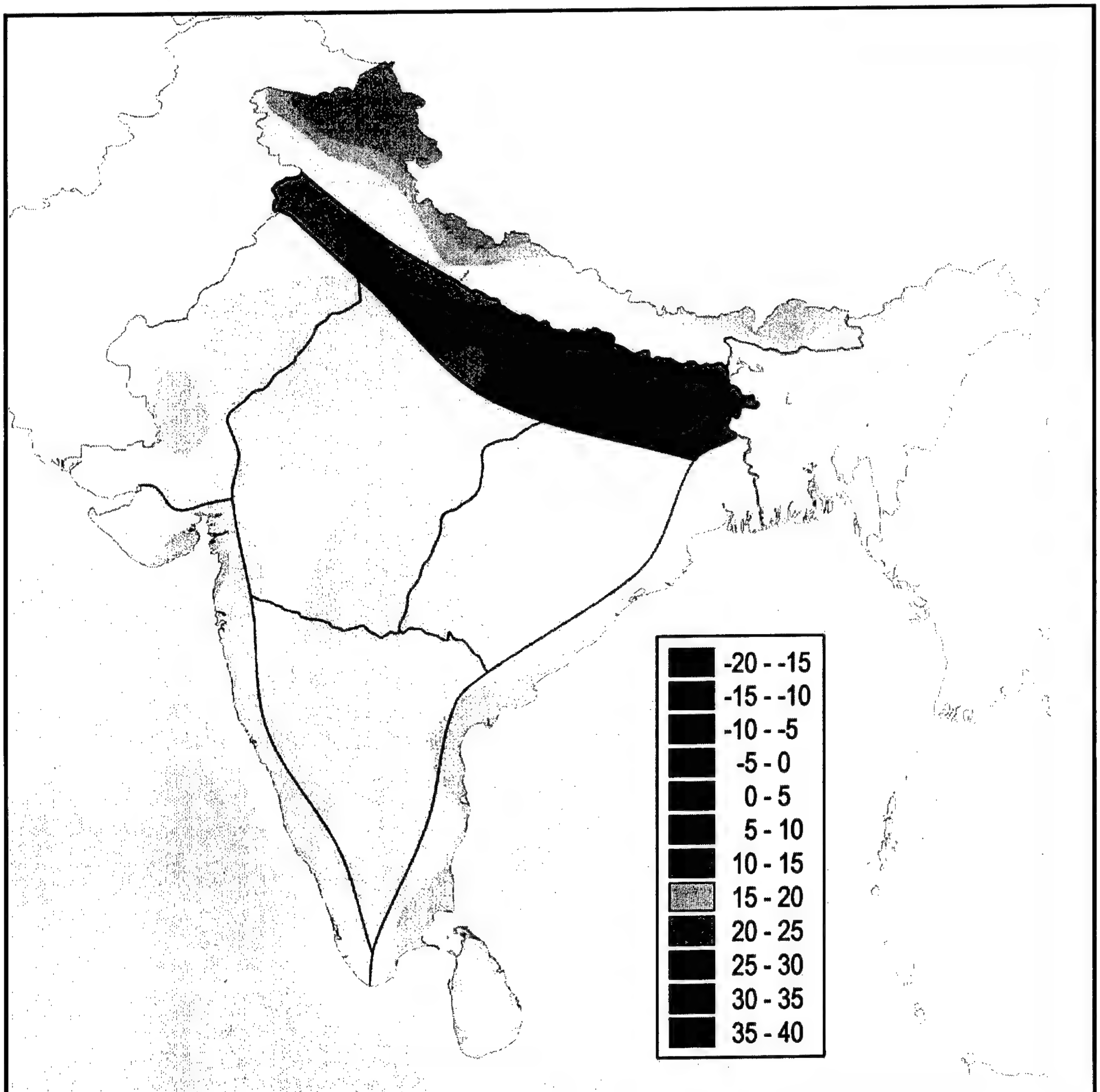


Figure 6-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be lower.

HIMALAYAS

This chapter describes the geography, major climatic controls, special climatic features, and general weather by season for the Himalayan Mountain Range that lies within Nepal, Bhutan, the Indian province of Sikkim, and the disputed territories of Jammu and Kashmir.

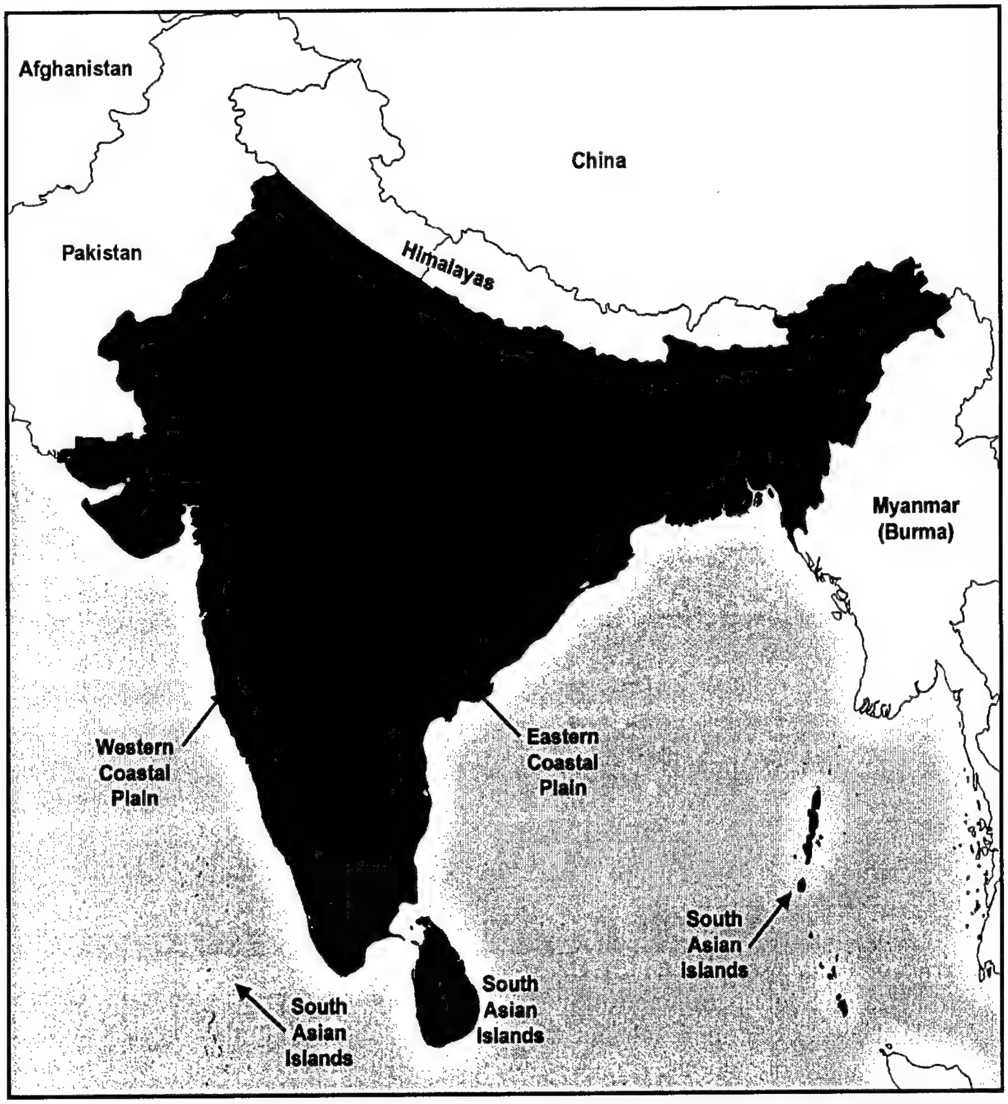


Figure 7-1. Himalayas. This figure shows the location of the Himalayas (highlighted in yellow) in relation to the other South Asia zones.

List of Topics

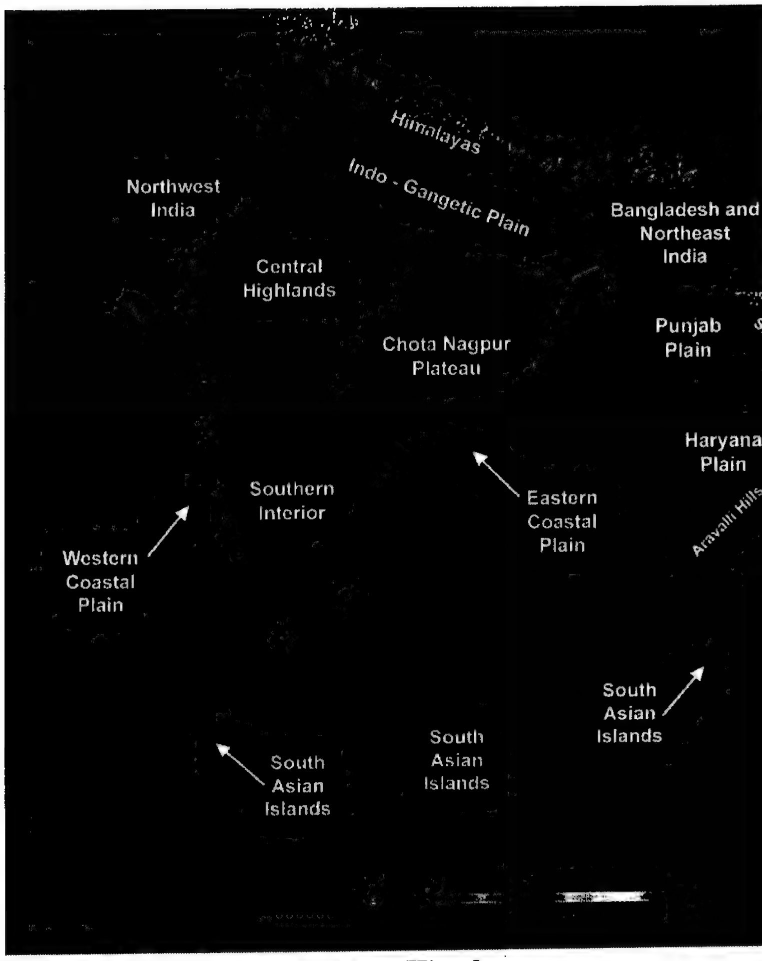


Figure 7-2a. Topography of the Himalayas.

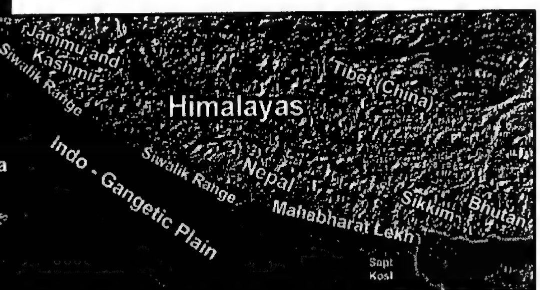


Figure 7-2b. Expanded View of the Topography of the Himalayas.

Topography

Boundaries. The region of the Himalayas includes Nepal and Bhutan, the Indian province of Sikkim, and the disputed territories of Jammu and Kashmir. The boundary begins at the extreme northern point of the disputed portion border between Kashmir and China. The boundary continues southeast along the Chinese-Indian border, the Chinese-Nepalese border, and the small border between China and Sikkim. Bhutan is at the eastern end of the region. The southern boundary of the region begins at the southwestern corner of Bhutan and follows the 1,000-foot (330-meter) elevation contour along southern Sikkim and Nepal. The western boundary continues from the southwestern corner of Nepal, along the 1,000-foot contour, through Jammu and Kashmir, to just west of the city of Dianagar, on the disputed border with Pakistan.

Major Terrain Features. The Himalayas claim 10 of the 11 highest mountains in the world. With a total of 20 peaks higher than 25,000 feet (7,600 meters), the Himalayas rightfully claim the title "The Roof of the World." As the Indian subcontinent is shoved beneath the Tibetan Plateau, the highest mountains are formed at the leading edge of the collision zone. Heights gradually decrease south of the collision zone. Ridge lines are oriented west-northwest to east-southeast in western half of the region and west to east in the eastern half. The topography of the Himalayas is as diverse as it is majestic. From the northern fringes of the Indo-Gangetic Plain in the south, progressively higher ranges are interspersed with deeper valleys. For this study, the Himalayan region is divided into two primary sections, the hills and the mountains.

Hills. Hills encompass the southern half of the Himalayas and ranges in elevation from 1,000 feet (300

meters) to nearly 13,000 feet (4,000 meters). Numerous minor ranges of hills and small mountains are in this section from Bhutan to Kashmir, but the two primary ranges are the Siwaliks (also known as the Churia Range or the Inner Himalayas) and the Mahabharat Lekh. Both are primarily in Nepal. The Siwaliks are 4,000-6,000 feet (1,200-1,800 meters) high in Nepal and 5,000-9,000 feet (1,500-2,700 meters) high in Bhutan. The Mahabharat Lekh range from 8,000-13,000 feet (2,400-4,000 meters) and stretch the length of Nepal.
Numerous intermontane valleys are between the hills and mountains of the region. Kathmandu Valley lies in the east-central part of Nepal at an elevation of about 4,000 feet (1,200 meters). Kathmandu is surrounded by 7,000-foot to 9,000-foot (2,100 to 2,750 meters) peaks of the Mahabharat Lekh.

Mountains. The Himalayan Mountains (also known as the Great Himalayas) begin in the Pamir Knot region of Central Asia and form a southeastward crescent more than 1,500 miles (2,500 km) long. The eastern end of the Himalayas anchors the Tibetan escarpment. The 200 miles (320 km) of the Himalayas east of Bhutan are not included in this chapter. The Himalayan region is considered the range of mountains between the Indus and Brahmaputra Rivers. The northwestern Himalayas are 20,000-24,000 feet (6,100-7,300 meters) tall in Kashmir. The heights gradually rise to 26,000-29,208 feet (7,900-8,848 meters) in northeastern Nepal. East of Sikkim, the Himalayas average 19,000-23,000 feet (5,800-7,000 meters). In northeastern Nepal, 7 of the 8 highest mountains in the world are within 75 miles (125 km) of Mt. Everest.

The are several other mountain ranges in the region. The Ladakh Mountains are north and east of the Himalayas and are oriented northwest-southeast in northeastern Kashmir. Heights in this 180-mile (300-km) long range average 18,000-20,000 feet (5,500-6,100 meters), and rise as high as 22,060 feet (6,724 meters). Just north of the Ladakh Mountains, the Karakoram Mountains intrude into extreme northern Kashmir. At 25,172 feet (7,672 meters), Saser Kangri is the highest peak in this part of Kashmir. Another lesser range, the Pir Panjal Mountains are south and west of the western Himalayas. The Pir Panjal are also separated from the Himalayas by the Vale of Kashmir, the Jhelum River valley. This 200-mile (320-km) long range has heights of 14,000-18,000 feet (4,300-5,500 meters). Two minor southern spurs of the Himalayas are in Bhutan. The Black Mountains, in central Bhutan, average 5,000-9,000 feet (1,500-2,700 meters) and form an important watershed between the Mo and Drangme Rivers. The Donga Mountains, in northeastern Bhutan, average 12,000-16,000 feet (4,000-4,900 meters).

Rivers and Drainage Systems. There are countless streams and rivers fed by snow melt from the Himalayas. The Indus River originates in southwestern Tibet and flows westward through central Kashmir in the valley between the northern Himalayas and the southern slopes of the Ladakh Mountains. As the Himalayas rose around it, the Indus cut deep gorges in the mountains over the last 60 million years. The Indus enters Pakistan just south of the Karakorums and then turns south before it empties into the Arabian Sea. The Chenab River, another major river of Kashmir, originates in the Vale of Kashmir, the valley between the Himalayas and the Pir Panjal Mountains, and continues to the southwest through Pakistan. The Jhelum River also originates in the Vale of Kashmir and flows through the city of Srinagar. Two other rivers of northern India originate in the Himalayas: the Yamuna and Ganges River. The Yamuna flows through New Delhi, and the Ganges is the most important waterway of northern India. The Yamuna eventually merges with the Ganges and they both drain into the Bay of Bengal in Bangladesh. From west to east, there are three rivers that flow from Nepal through north-central India, the Ghaghara, the Narayani, and the Sapt Kosi. All eventually merge with the Ganges. The Tista River flows through central Sikkim before it merges with the Brahmaputra River. The Mo and Drangme Rivers, two main river systems of Bhutan, originate in the Himalayas and merge with the Brahmaputra River.

Major Climatic Controls

Asiatic (or Siberian) High. This strong, cold-core anticyclone controls the weather over much of Asia from October to April. The Himalayas act as a barrier and protect the subcontinent from the harshest effects of this shallow feature. Modified air does intrude into India from the east around the southern periphery of the Tibetan plateau. Outflow from this feature creates a lee-side trough on the southern side of the Himalayas that provides a storm track for systems that move out of southern Europe.

North Pacific High. This semipermanent anticyclone plays an important role in the monsoon seasons of South Asia. The ridge axis migrates north and west in Northern Hemisphere summer (May through October) and east and south in winter (November to April). The high is linked to the position of the ET, which marks the boundary between the northeast and southwest monsoons.

Tibetan Anticyclone. This Northern Hemisphere (southwest monsoon) upper-air feature forms as the result of latent heat of condensation from widespread convection over Myanmar in late April and early May. Intense solar radiation and surface heating on the Tibetan plateau causes the high to shift from Myanmar to Tibet by late May. This upper-air cell is important during the southwest monsoon because tropical cyclones, monsoon depressions, and other disturbances develop along its southern edge, especially in the Bay of Bengal. The anticyclone acts as an outflow mechanism for convection associated with the monsoon trough. The anticyclone is reinforced by the deep easterlies that reach almost to the foot of the Himalayas by July and by the deep westerlies of the Northern Hemisphere mid-latitudes. Also, since this anticyclone interacts with the subtropical ridge aloft, its position varies east and west. If the position shifts eastward of 90° E, the result is severe drought.

Heavy Tibetan snow cover that accumulates during the southwest monsoon lowers surface temperatures over the plateau by mid-August. Energy previously used for surface heating is now required to melt snow and evaporate runoff. Although surface temperatures cool immediately, cooling aloft lags 1-2 months behind. The Tibetan plateau is snow-free 80 percent of the time during the early southwest monsoon months. By October, the anticyclone weakens and disappears because the surface "trigger" is eliminated and upper-level westerlies move southward over the Tibetan plateau.

Australian High. This cold-core high sets up over Australia during Southern Hemisphere winter (May through October). The Australian high is strongest in July, when it is near 28° S 128° E, with a mean central pressure of about 1022 mb. It is neither as strong nor as persistent as the Asiatic high and is crossed regularly by disturbances and migratory high's. It helps regulate the outflow from the South Indian Ocean high and the South Pacific high and contributes to the tropical easterly jet (TEJ), which is a southwest monsoon feature. The outflow from this high also helps to push the equatorial trough (ET) northward to produce the southwest monsoon season in south Asia. This is the rainy season for South Asia.

Indian High. This thermal high sets up over the Indian peninsula on an irregular basis during the northeast monsoon (November to April). This high forms over the peninsula during a cold outbreak and stabilizes the weather over the whole area. This high does two different things. What it does depends on its strength and position. Although always weak, when the high is at its strongest, it tends to block low pressure systems from the track across the south foot of the Himalayas by displacing the lee-side trough that is typically in place. Obviously, the farther north the high develops, the more likely it is this will happen. When the high is weakest, it has the opposite effect. It tends to intensify the lee-side trough at the southern foot of the Himalayas without shifting it out of position. This provides a pipeline for lows out of Europe, which use the subtropical jet to zip through the region. When the Indian high is weak it enhances western disturbances.

South Indian Ocean (Mascarene) High. This year-round high shifts north and south with the sun. At its strongest during Southern Hemisphere winter, it provides cross-equatorial flow from April to October (reflected in both the Somali jet and the equatorial westerlies). This warm, moist flow contributes significantly to the ET shift to the north, which brings the southwest monsoon to South Asia.

Asiatic Low. This massive thermal low, centered over Pakistan in summer, anchors the western end of the ET. As the Asiatic low deepens, it draws the ET and the southwest monsoon northward across the subcontinent. It is strongest in July, when its central pressure averages 994 mb. Fluctuations in the position and strength of the Asiatic low cause oscillations and waves along the ET. As the Asiatic low weakens and fills in late summer, the ET quickly retreats south.

Australian Low. This thermal low forms over Australia during Southern Hemisphere summer and strengthens the pressure gradient between Asia and Australia. The Australian low is only present during the austral summer and is strongest in January, with a mean central pressure

of 1006 mb. It breaks up the smooth outflow of the South Indian Ocean and South Pacific highs. This disrupts the tropical easterly jet (TEJ), which disappears, and helps draw the ET south of the equator. This brings the northeast monsoon and drier weather to South Asia.

India-Myanmar Trough. This northeast-southwest oriented trough develops in the Bay of Bengal and is a southwest monsoon feature (May to October). Partly caused by friction-induced convergence of southwesterly flow and partly supported by the Asiatic low, this trough intensifies the TEJ over the Bay of Bengal and provides a preferred location for the development of monsoon depressions.

Monsoon Climate. For South Asia, the monsoon climate means the subcontinent has distinct rainy and dry seasons. Under the northeast monsoon (November to April), the region is largely dry. Under the southwest monsoon (May though October), it is rainy. Onset of the rainy season normally occurs at Kathmandu around the 10th of June. The rainy season is much shorter in the Himalayas than in the rest of South Asia. The southwest monsoon typically withdraws from Kathmandu by early October.

Equatorial Trough (ET). This convergence zone marks the boundary between the northeast and southwest monsoon. Also called the monsoon trough in this region, it is a zone of instability that triggers precipitation. This boundary zone shifts north and south with the sun in response to a complex array of atmospheric interactions. When it shifts north (May through October), the southwest monsoon takes over in South Asia. When it shifts south (November through April), the northeast monsoon assumes control.

Special Climatic Controls

Elevation. Nowhere else on Earth does elevation play as significant a role in climate as the Himalayan Mountains. In winter, the Himalayas are a barrier between the bitterly cold air of the Asiatic high and the more moderate air across the subcontinent. Northern Indian stations and other cities just south of the Himalayas average 16 Fahrenheit (9 Celsius) degrees warmer than inland stations in China, at the same latitude. Conversely, during the southwest monsoon, the Himalayas stop the northward progression of the ET. Most of the monsoonal moisture is deposited on the southern slopes and foothills of the Himalayas. There is also a corresponding increase in rainfall in the plains which lead up to the foothills. Elevation also influences the mean temperature profile of stations in the region. Kathmandu, the capital of Nepal, is closer to the equator than Tampa, Florida, however, because it is at 4,420 feet (1,347 meters), the mean temperature profile is classified as cool and temperate.

Himalayan Lee-Side Trough. This feature forms to the south of the Himalayas when northerly flow crosses the ridge line. The lee side trough is particularly endemic to the winter season because of the northerly outflow from the Asian high. European lows that travel along the subtropical jet in northern India interact with the trough and regenerate. Additionally, since the trough is maintained by strong, northerly flow, intense foehn winds are commonly found in the vicinity of the trough. Mountain wave turbulence is also commonly experienced between the ridge axes and the trough. As soon as the northeast monsoon ends, the trough breaks down and disappears.

Subtropical Jet (STJ). This jet is significant in this region in the northeast monsoon season (November to April) when its southern branch slips south of the Himalayas. Low pressure systems out of Europe (western disturbances) ride the jet through the northern part of India, Bangladesh, and East India. As the subtropical ridge axis moves north with the approach of the southwest monsoon, the STJ moves north.

Western Disturbances. These develop from short waves in the larger, long-wave pattern. They move from west to east and are often most easily observed at 500 mb. In South Asia, particularly in winter (November through April), several waves move across the northern portions of the subcontinent and give rise to cloudiness and precipitation. The STJ, south of the Himalayas in winter, provides transport to rapidly move these waves into and through the area.

Hazards for All Seasons

Aircraft Icing. Generally, the freezing level is so high that icing is not much of a threat to aircraft flights below 10,000 feet. Light to occasionally moderate mixed icing can occur above the freezing level. Severe mixed icing occurs in the vicinity of thunderstorms. Severe icing is also found below 10,000 feet in winter in the vicinity of western disturbances in the region.

Turbulence. Severe and extreme mountain wave turbulence are common in the Himalayas and primarily occur when the STJ and strong westerlies blow perpendicular to ridgelines. Cloud streets of altocumulus standing lenticular and cirrocumulus standing lenticular on satellite photographs are frequently the only signs of mechanical turbulence. Aircraft in the region often experience extremely strong updrafts on the western slopes and downdrafts on the eastern side of the ridgeline.

Floods. Floods occur in the Himalayan region for several reasons. Himalayan rivers and streams originate in mountainous glaciers and lakes. At the highest elevations, they flow rapidly through narrow channels, and frequently overflow their banks. As they reach lower elevations, their channels widen and the rivers flow with greater depth. Landslides frequently cause rock debris and detritus to form temporary dams that create temporary lakes. As the rivers continue to cascade down the mountain, the dam-formed lakes rise. When the dam is breached, the result is an abnormally high flood with the potential for catastrophic damage. Also, large-scale deforestation and topsoil erosion result in more damaging floods. The capacity of the ground to retain moisture is diminished, and when the inundating rains of the southwest monsoon occur, extremely heavy floods result. Ice moraines dam the water trapped beneath mountain glaciers. This trapped water causes tremendous pressure to build on the moraines, and when the moraine melts or breaks down, the trapped water is released and blasts through the river channel.

Elevation. Altitude affects nearly every element of human activity. The unusually warm temperatures at high elevations result in extremely high pressure altitudes. Because of the thin air and high pressure altitude, aircraft require much longer takeoff and landing distances. Thin air also impacts parachute operations. Parachutists drop faster, and land harder in the thin mountainous air. Vehicles and other machinery that operate with carburetors need to be specially modified to operate in the thin air. Personnel need to be educated and acclimatized to the effects of high-altitude sickness. Hypoxia (oxygen deprivation) can be life-threatening.

Avalanches. During the hot season, the winter snow pack begins to melt and occasionally breaks loose. The long, steep incline of the Himalayas amplifies the resultant avalanche. Since snow continues to fall at the highest elevations of the Himalayas through the southwest monsoon, the region is susceptible to avalanches most of the year.

Blizzards. The combination of high winds and heavy snowfall make the highest elevations of this area extremely hazardous. Blizzards occur primarily in the winter, but can occur at any time of year at higher elevations with little warning. Swirling winds cause the visibility to quickly drop to zero.

Foehn/Bora Winds. Strong low-level winds occur primarily on the lee of mountains in the winter and early hot season when the westerlies are strongest. Himalayan foehns are stronger and more dangerous because they have tremendous potential energy. As the foehn wave bottoms out, the corresponding rise in temperature and drop in humidity is dramatic. Occasionally, during the late winter and hot season, stronger foehns cause a rapid melt of the snow pack that results in avalanches and mud/landslides. Boras occur when strong winds (primarily westerlies) are forced through narrow, steep canyons and river valleys. The venturi effect of squeezing strong winds through tight canyons results in highly amplified wind speeds. Strong boras occasionally cause landslides and avalanches.

Obscured Peaks. Cloud cover frequently obscures the Himalayan peaks. Aircrews flying through this region should exercise extreme caution, particularly on the windward sides of ridgelines. Inaccurate and unreliable aeronautical charts contribute to the hazardous nature of this region. Cloud cover usually dissipates and flight visibility improves dramatically on the lee side of the ridge.

Winter

General Weather. By December, the 500-mb subtropical ridge moves to 14° N, and the STJ shifts south of the Himalayas. Mid-latitude westerlies dominate the region. The STJ brings transitory shortwaves through the region every 3-5 days and produces more precipitation in the western Himalayas than in the east; the area just east of Srinagar receives about 5 times as much precipitation in winter as Darjeeling. Large amounts of snow falls along the western and southwestern slopes of the mountains. The western Himalayas show an increase in snowfall amounts in December and receive the most snow in January and February.

The Himalayas block the extremely cold, continental outflow from the Asiatic high from India. Modified air occasionally leaks through the Hindu Kush region into the Indus River valley along the western periphery of the Himalayas. Additionally, modified air passes into extreme northeastern India along the eastern periphery of the Himalayas. As the weak, northerly flow crosses perpendicular to the Himalayas it forms a lee side trough south and parallel to the mountains. This trough creates a cyclogenesis zone for transitory lows that are brought into the region by the prevailing westerlies.

Sky Cover. Figure 7-3 shows occurrence rates of ceilings below 5,000 feet at representative stations. Many stations at higher elevations experience an afternoon maximum in the frequency of ceilings. This is especially true for those stations located above a river valley. Low ceilings form in the river valley below the station during the early morning and lift up the valley as the inversion breaks by late morning. Kashmir and the western Himalayas are exposed to the full brunt of the storm track and consequently, receive a higher amount of cloudiness. Winter is the cloudiest season of the year for Kashmir and the least cloudy for the rest of the Himalayas.

Srinagar, the capital of Kashmir, is on the western slopes of the Himalayas and is the westernmost of three northern Kashmir stations. However, Srinagar receives ceilings below 5,000 feet 50-65 percent of the time due mainly to western disturbances and localized wind effects. Farther eastward, Dras is on the lee-side of the Himalayas in winter and receives low ceilings less than 20 percent of the time. By the time migratory systems reach Leh, on the windward side of the Ladakh Mountains, they have very little low-level moisture. Leh receives ceilings below 5,000 feet less than 10 percent of the time.

Elevation is a key element of how often a site has low ceilings. In northern Uttar Pradesh, along the western slopes of the Siwalik Mountains, Dehra Dun and Mussoorie are separated by less than 6 miles (10 km). Mussoorie is at an elevation three times as high as Dehra Dun. Mussoorie has ceilings below 5,000 feet up to 36 percent of the time, 3-4 times as often as Dehra Dun. Migratory western disturbance systems and localized wind effects create upslope conditions to cause this. The occurrence rate of ceilings below 5,000 feet gradually rises across Nepal from 17 percent of the time at Surkhet to nearly 30 percent of the time at Dhankuta. Darjeeling has more cloudiness than usual for its area because of the Mahananda River a ready moisture source. Darjeeling has ceilings below 5,000 feet 35-40 percent of the time in the morning and 50-60 percent of the time in the afternoon.

Bhutan has low ceilings most frequently in the western portion of the country. In the southwestern corner of Bhutan, near the Torsa River valley, ceilings below 5,000 feet occur 30-40 percent of the time in the afternoon. Thimphu, the capital, has mainly dry and cloud-free winters; low ceilings occur approximately 10-20 percent of the time. Between the Mo River and the Black Mountains, low ceilings occur 15 percent of the time at the northern end of the river, and 30 percent of the time at the southern end near the Duars Plain. The remainder of the country east of the Black Mountains has low ceilings less than 10 percent of the time.

Most of the stations across the Himalayan region record ceilings below 1,000 feet less than 10 percent of the time. A handful of stations between Simla and Mukteswar record ceilings below 1,000 feet up to 15 percent of the time. Darjeeling is the cloudiest station in the region, with ceilings below 1,000 feet up to 40 percent of the time. Even though Darjeeling is the cloudiest station, winter is still its least cloudy season.
diurnal influences.

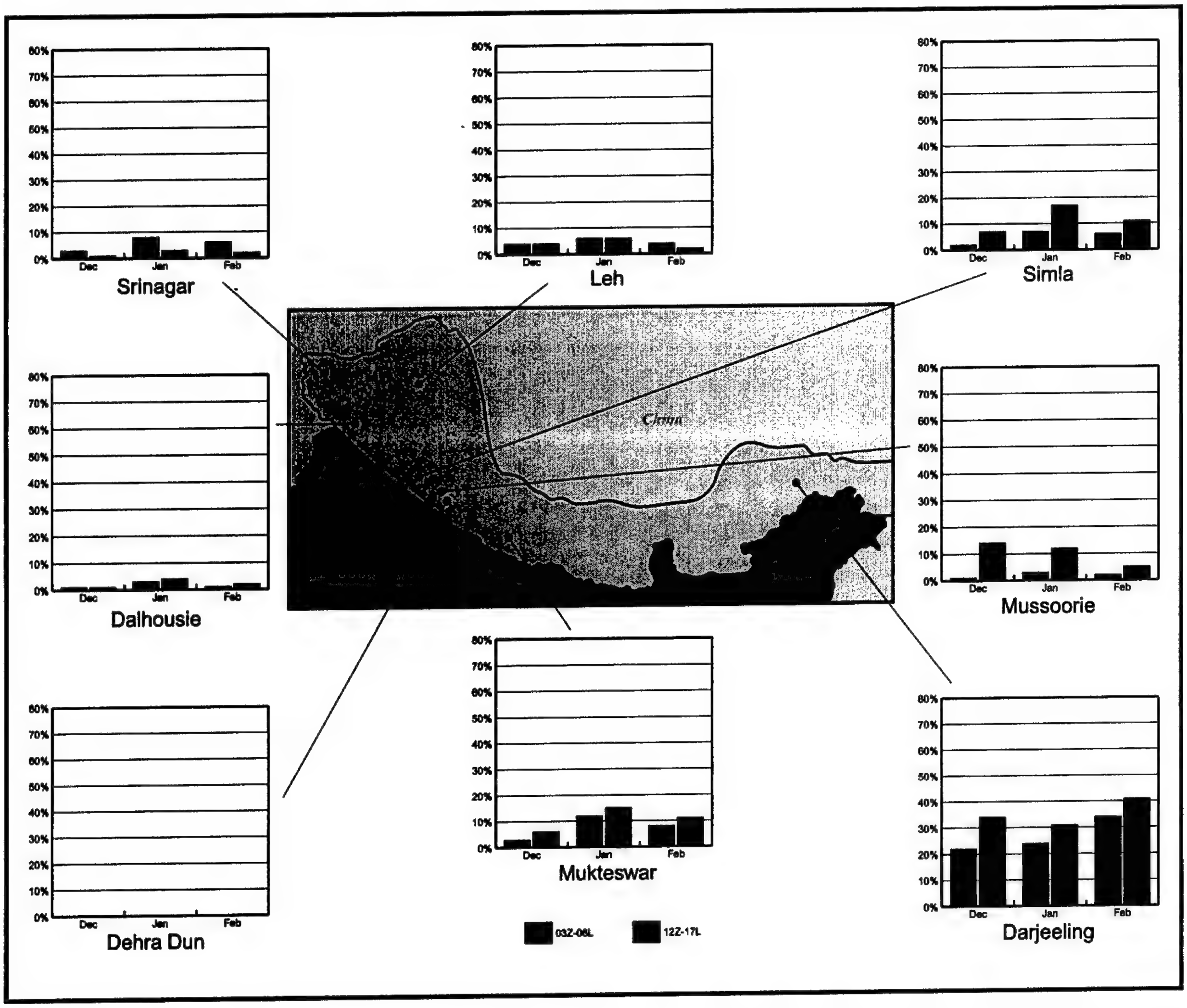


Figure 7-3. Winter Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility across northern Kashmir progressively improves west-east with each successive mountain range. Diurnally, the worst time for visibility across Kashmir is during the early morning hours. The westernmost site, Srinagar gets the full brunt of migratory systems and averages visibility under 2 1/2 miles (4,000 meters) more than 40 percent of the time. On the other side of the ridge, Dras gets it about 25 percent of the time. Farthest inland, Leh reports visibility below 4,000 meters 10-15 percent of the time. To the southeast, across Himachal Pradesh, Mandi averages visibility under 4,000 meters 50 percent of the time in January and February. Mandi is on the southwestern (windward) slopes of the Siwaliks. Fewer, and weaker, migratory systems cause this percentage to quickly drop to 12 percent of the time in March.

Upslope conditions and a multitude of mountain streams and other localized moisture sources cause a high frequency of low visibility across Nepal. Additionally, since a majority of the population congregates in the few, fertile intermontane basins, visibility is degraded by pollution. Two of the worst cities are Bhairawa and Kathmandu. Bhairawa is on the southern slopes of the Siwaliks and along a tributary of the Rapti River. On December and January mornings, Bhairawa has visibility below 4,000 meters 90 percent of the time. The upslope condition, combined with a ready moisture source, is conducive for fog formation. The fog rapidly clears, but visibility is still degraded on 30-40 percent of the winter afternoons. Kathmandu, has degraded visibility 90 percent of the time on December and January mornings. This is a result of stagnant air trapped in the intermontane basin beneath a strong inversion. Visibility rapidly improves when the inversion breaks by late morning. By afternoon, the visibility is degraded less than 5 percent of the time. Similarly poor visibility is also experienced in the Bharatpur and Dang intermontane basins of Nepal.

Darjeeling has fog that restricts visibility below 4,000 meters 35-40 percent of the time in the morning and 60 percent of the time in the afternoon. Stratus that lifts out of the nearby river valley as the inversion breaks brings fog and drizzle to Darjeeling in the afternoon. Southern Bhutan is also susceptible to upslope fog and stratus. The southern slopes of the Black Mountains have visibility below 4,000 meters 10-20 percent of the time in the mornings and 25-35 percent of the time in the afternoon. The only parts of interior Bhutan that record as much fog are near the main rivers. Even though Thimphu is on the Wang River, it has reduced visibility only 5-10 percent of the time. Persistent northerly winds that blow through the valley keep this small urban center clear. Figure 7-4 illustrates the seasonal percent frequency of visibility below 4,000 meters in the region.

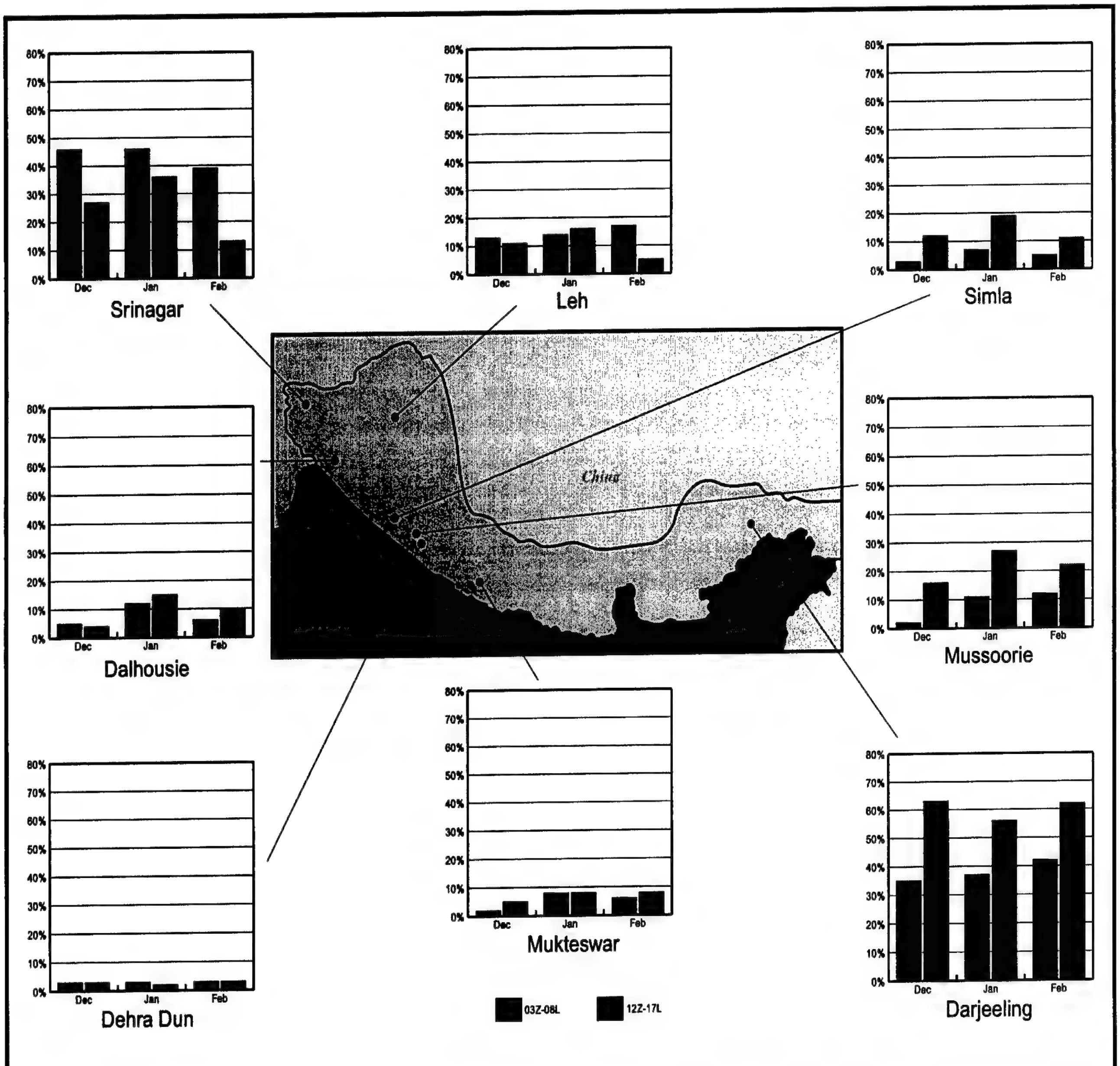


Figure 7-4. Winter Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The terrain of the Himalayas overwhelms the effects of large-scale wind patterns on the region. Nearly every location is susceptible to channeling, venturi winds, foehns, and localized mountain/valley winds. The large-scale flow is westerly, and when the terrain is oriented west-east, it tends to reinforce prevailing flow. When the terrain is oriented north-south, it determines the local winds, no matter how strong the prevailing flow becomes.

Dehra Dun is prone to a nocturnal drainage wind of 5-8 knots from a canyon northeast of the city. Since Dehra Dun is on the southern slopes of the Siwaliks, the terrain effect is moderated. By the time the inversion breaks, the prevailing westerly winds dominate the wind regime. Surkhet gets a northerly mountain breeze of 5-8 knots 60-70 percent of the time in early morning. Surkhet lies in a west-east oriented valley between the Siwalik and Mahabharat Lekh Mountains. This topography reinforces the predominantly westerly component of the winds during the afternoon. Westerly winds at 5-8 knots occur 80 percent of the time on January and February afternoons. By evening, the inversion is reestablished and the northerly mountain breeze returns.

Kathmandu is representative of stations in intermontane basins. The city has calm winds virtually 100 percent of the time in late evenings and early mornings. A strong inversion caps the basin and prevents gradient-level winds from mixing to the surface. After the inversion breaks, westerly winds occur at Kathmandu 40-60 percent of the time in the afternoon. Figure 7-5 shows January surface winds at different locations around the region.

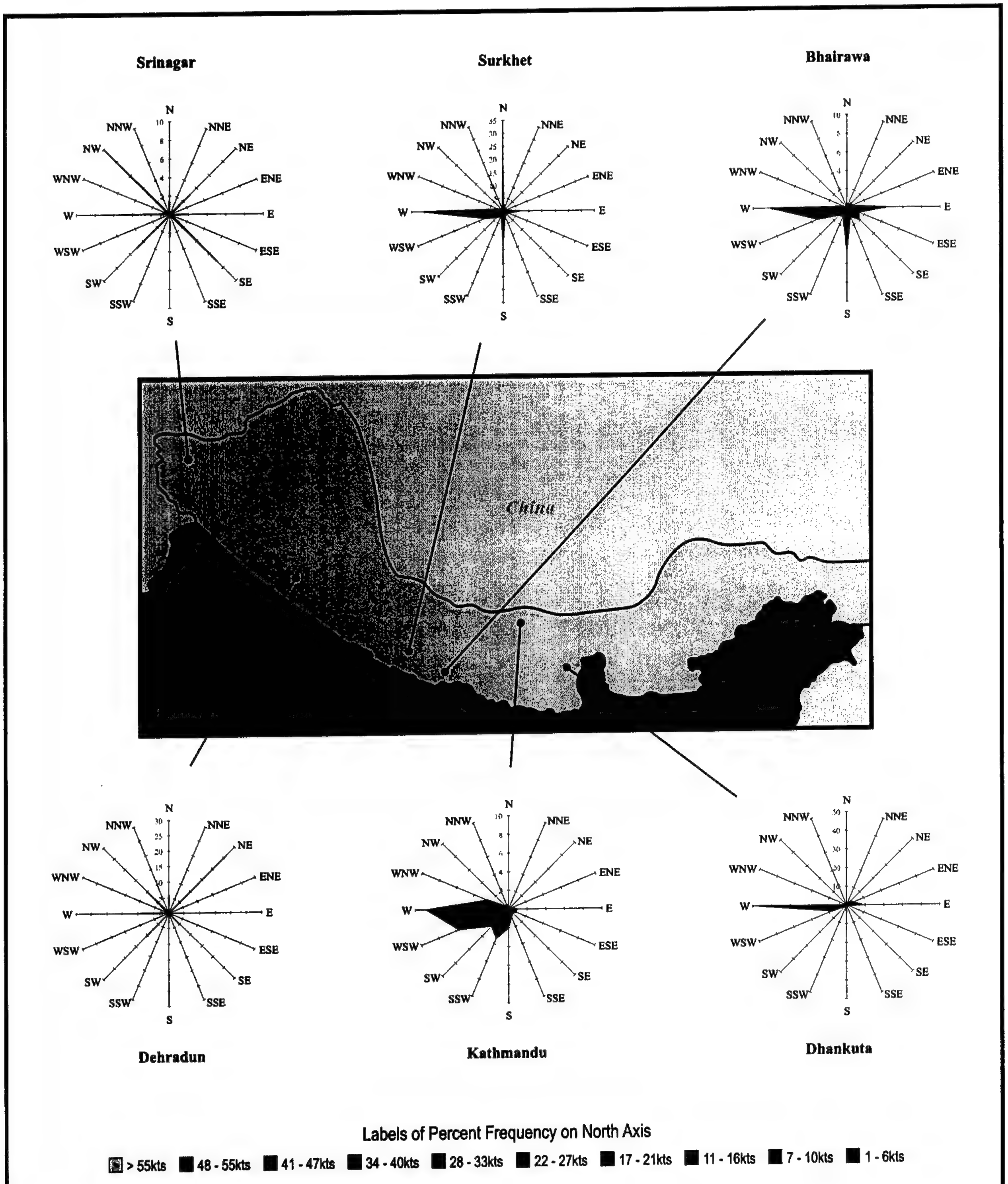


Figure 7-5. January Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Level Winds. By December, the subtropical jet (STJ) lies just south of the Himalayas. The STJ is strongest in January and February and is best represented at 200 mb with a central core of 75-100 knots. Wind speeds at 300 mb exceed 90 knots about 5 percent of the time and exceed 120 knots less than 2 percent of the time. At 500 mb and below, wind speeds generally are less than 25 knots. To varying degrees that depend on elevation, terrain effects influence wind speed and direction at nearly every upper-level pressure surface from 850 mb to 400 mb. In the Siwalik Mountains, the pressure at the surface ranges from below 850 mb to just above 700 mb. The surface pressure level ranges from below 700 mb to above 500 mb in the Mahabharat Lekh and the Lesser Himalayas, and up to and above 400 mb across the main Himalaya Mountains. See Figure 7-6 for upper-level wind roses over Srinagar, India.

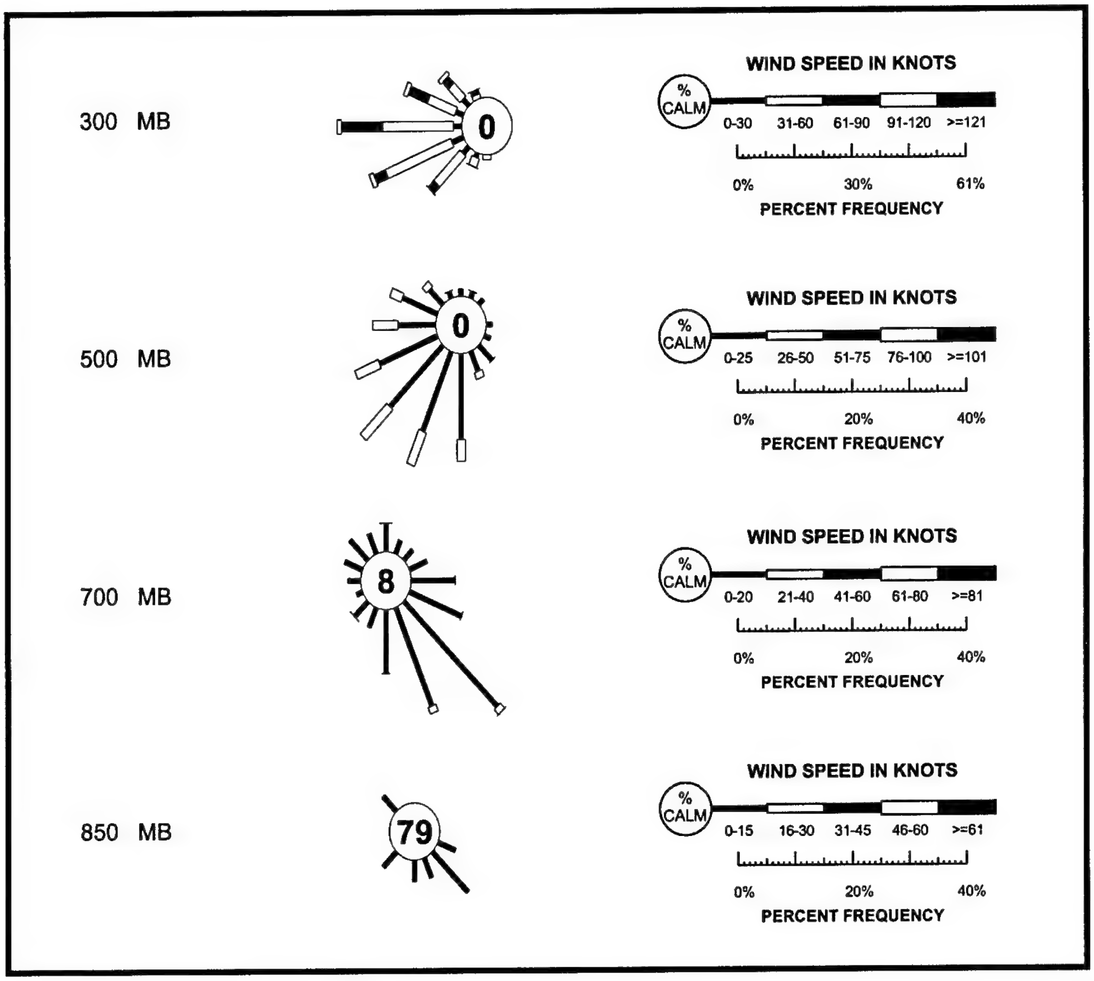


Figure 7-6. January Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb over Srinagar, India.

Precipitation. Fast-moving, migratory systems drop most of their precipitation along the westernmost end of the Himalayas. Most of this area records at least 3 inches (76 mm) of precipitation during each of the winter months. The highest precipitation totals are recorded across north-central Kashmir, on the windward (western) slopes of the western Himalayas. In December, the area just east of Srinagar has more than 4 inches (102 mm) of precipitation. This amount doubles in January and February. Just west of Srinagar, the windward slopes of the Pir Panjal Mountains have 3 inches (76 mm) in December and 6 inches (152 mm) in January and February. The Srinagar intermontane basin between the two great ranges is comparatively drier; this basin records less than 1 inch (25 mm) in December and 2 inches (51 mm) in January and February. The lee side of the Himalayas near Leh is another area that has less than 1 inch (25 mm) in December and 2 inches (51 mm) in January and February.

Rain shadows are more pronounced across the western sections of the region than across the central and eastern sections. Across Kashmir, Himachal Pradesh, and Uttar Pradesh, the primary mountain ranges are farther apart and the intermontane valleys are broader. Across Nepal, there is no discernible rainshadow effect since the Siwaliks are only about 22 miles (35 km) away from the Mahagharat Lekh, however, a strong rainshadow exists between the Mahabharat Lekh and the main Himalayas. Because these two mountain ranges are separated by 62 miles (100 km), there is a precipitation disparity of more than 50 percent between the windward and leeward sides of the Great Himalayas. As systems travel eastward, they drop progressively less and less precipitation. Across most of eastern Nepal, Sikkim, and Bhutan, less than 1 inch (25 mm) of precipitation falls in December. In January and February, this amount increases to 1-2 inches (25-51 mm). Even the area around Mt. Everest records just slightly more than 2 inches (51 mm) at the height of winter. Precipitation almost exclusively falls in the form of snow. See Figure 7-7 for precipitation amounts in January for the region. Figure 7-8 depicts seasonal precipitation and thunderstorm days at various regional sites.

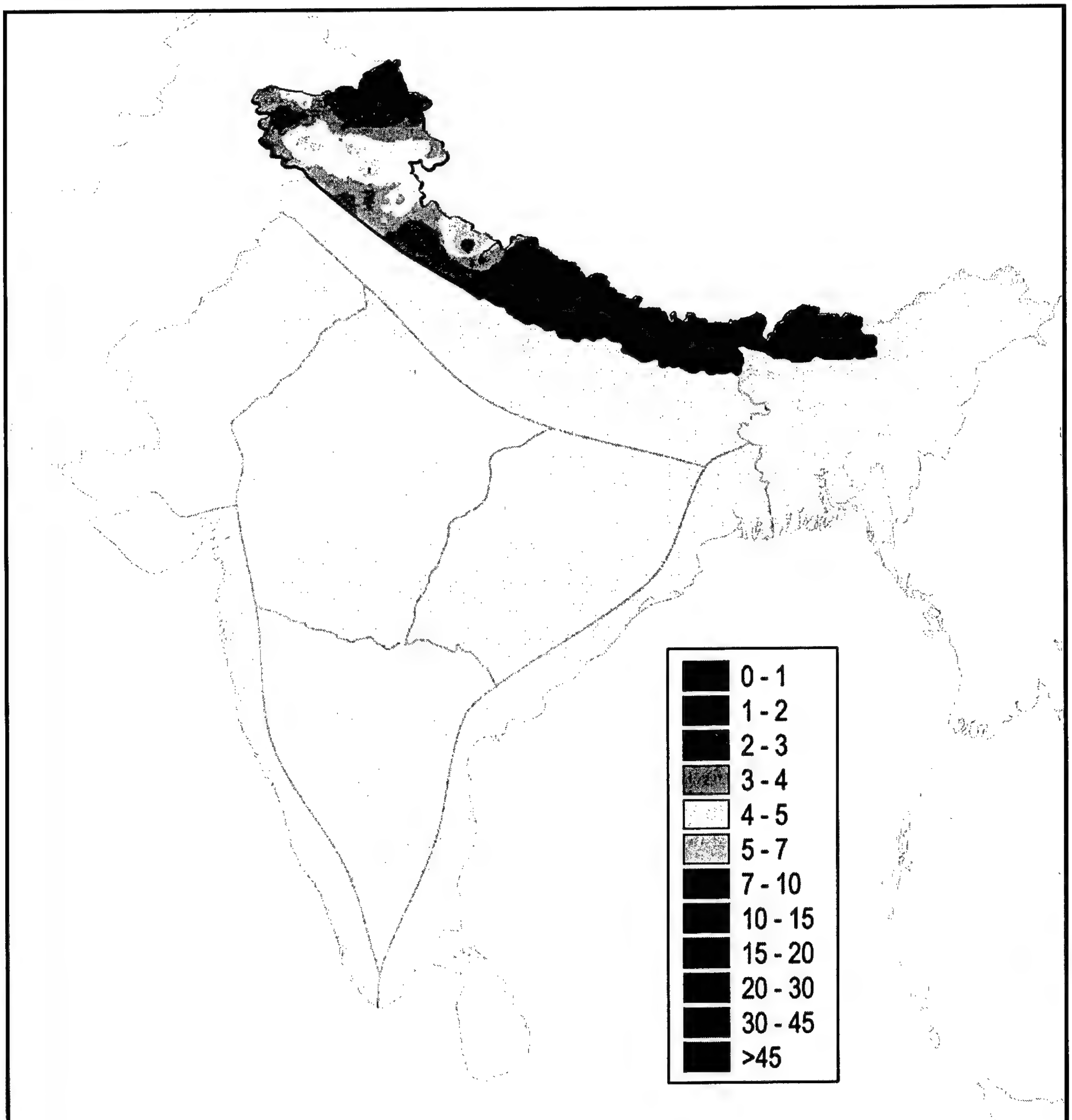


Figure 7-7. January Mean Precipitation (Inches). The isopleths depict the mean precipitation totals received during the most representative month of the winter season.

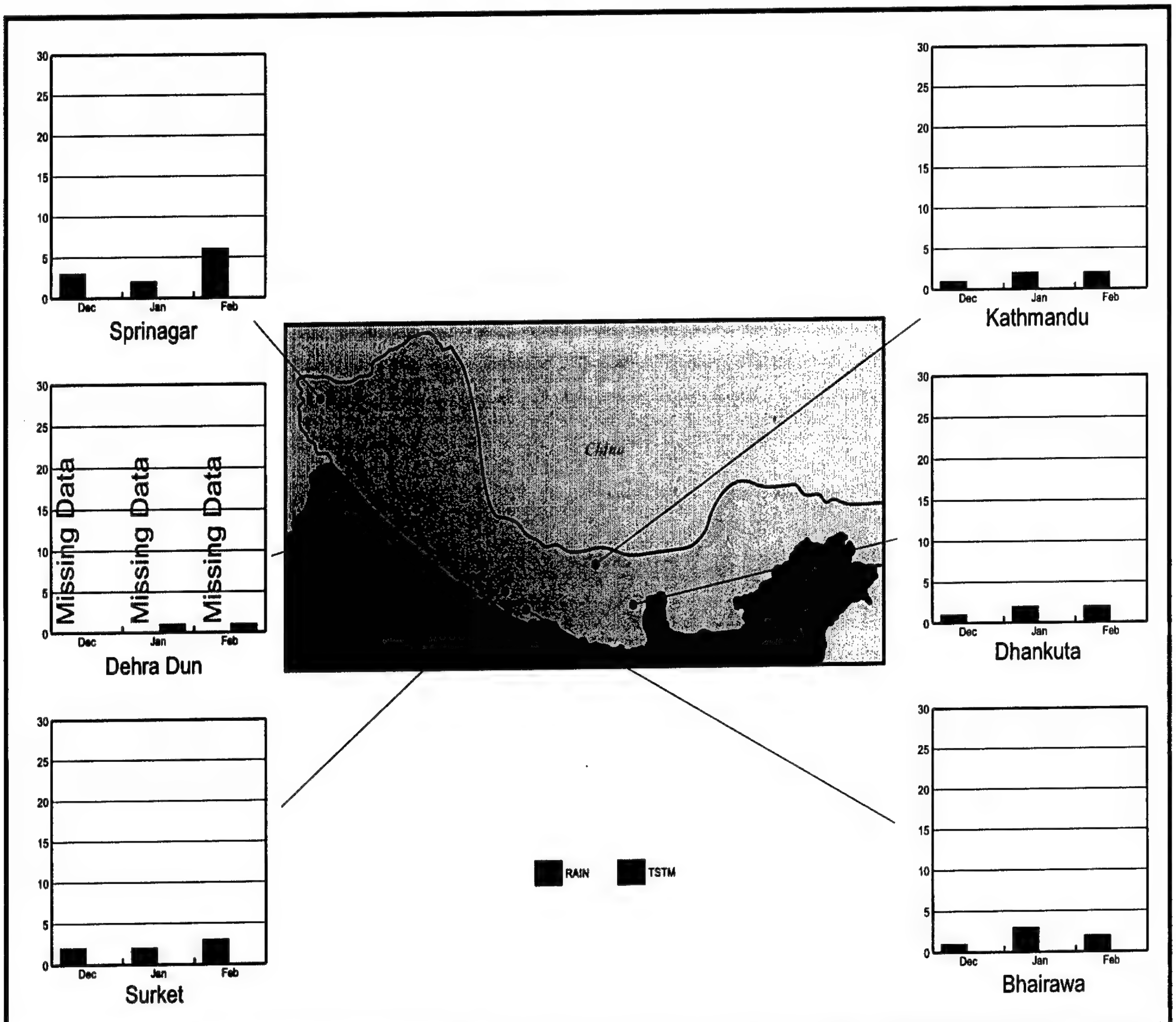


Figure 7-8. Winter Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of precipitation and thunderstorm days for representative locations in the region. Note: Rain in the legend pertains to the water equivalent of the snowfall.

Temperatures. Several factors moderate temperatures. The Himalayas block cold air intrusions from the Asiatic high. Also, the southerly latitude of the region increases the solar angle of incidence. Solar radiation is also enhanced because of the predominately clear, dry conditions of Nepal and Bhutan. Finally, the preponderance of foehn winds brings adiabatically-warmed air into the valleys and intermontane basins of the regions. See Figures 7-9 and 7-10.

The mean high for Srinagar ranges from 41° to 48°F (5° to 9°C) all winter. The high amount of cloud cover and the slightly more northerly latitude allow for the cool conditions at Srinagar. Approximately 155 miles (250 km) due east of Srinagar, on the other side of the Himalayas, Leh records mean highs of 30° to 36°F (-1° to 2°C). The warmest site in the region, Dehra Dun is not the southernmost or the lowest in elevation, but terrain has a significant impact. Mean highs at Dehra Dun are 66° to 69°F (19° to 21°C) all winter. Despite an elevation of more than 4,300 feet (1,300 meters), the winter mean highs at Kathmandu are extremely warm, 65° to 68°F (18° to 20°C). The large amount of cloud cover and an elevation of nearly 7,000 feet (2,100 meters) combine to cool the mean high at Darjeeling to 47° to 49°F (8° to 9°C). Even though it is at the southernmost part of the region, the north-south oriented ranges across Bhutan allow more intrusion of moderated continental air. The January mean high for Thimphu is 60°F (16°C).

Mean lows across Kashmir range from 24° to 30°F (-4° to -1°C) at Srinagar to 8° to 13°F (-13° to -11°C) at Leh. There is also a large difference in diurnal range at these two cities. Under high amounts of cloud cover and precipitation, the average diurnal range at Srinagar is approximately 17 Fahrenheit (9 Celsius) degrees. Leh is much less cloudy and has less precipitation. Correspondingly, it has a much larger diurnal range of about 23 Fahrenheit (13 Celsius) degrees. Mean lows at Kathmandu are 36° to 40°F (2° to 4°C). Darjeeling also has a small diurnal range. Because of the high occurrence of low ceilings and nearly steady, light precipitation, the diurnal range at Darjeeling is 11 Fahrenheit (6 Celsius) degrees. The mean low for Darjeeling are 35° to 37°F (2° to 3°C). Thimphu has a January mean low of 25°F (-4°C).

Extreme high and low temperatures are also moderated. At Srinagar, the extreme high is 75°F (24°C), while at Leh, it is 57°F (14°C). Dehra Dun recorded the warmest extreme high in the region, 95°F (35°C). Nearby Mussoorie, a city with much more cloud cover, precipitation, and a much higher elevation, had an extreme high of 77°F (25°C); a difference of 18 Fahrenheit (10 Celsius) degrees. Most stations in Nepal, including Kathmandu, have recorded extreme highs of 75° to 85°F (24° to 29°C). Kathmandu recorded an extreme high of 84°F (29°C). An extreme high of 72°F (22°C) was recorded at Darjeeling despite nearly perpetual cloudy conditions.

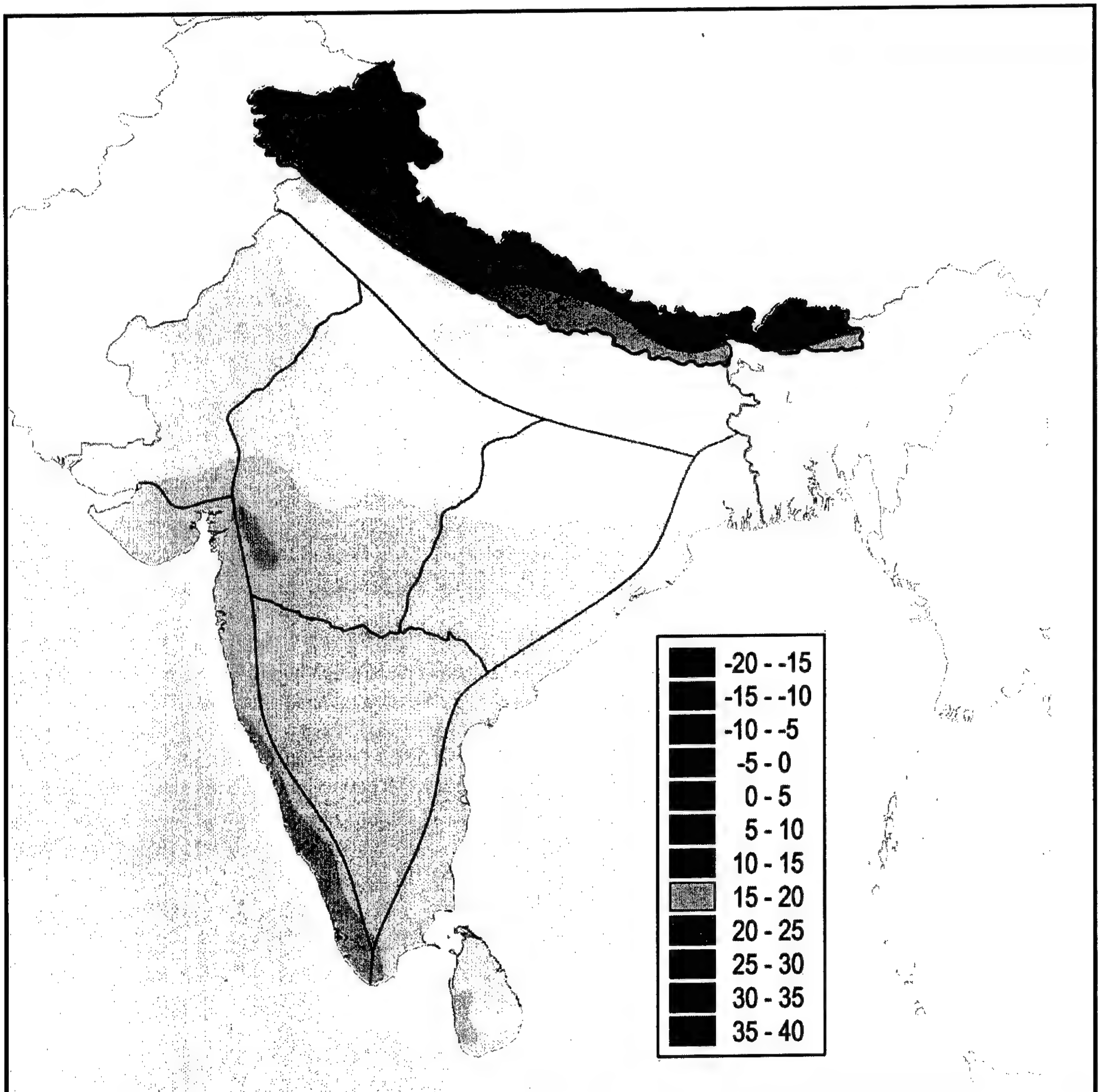


Figure 7-9. January Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for January. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

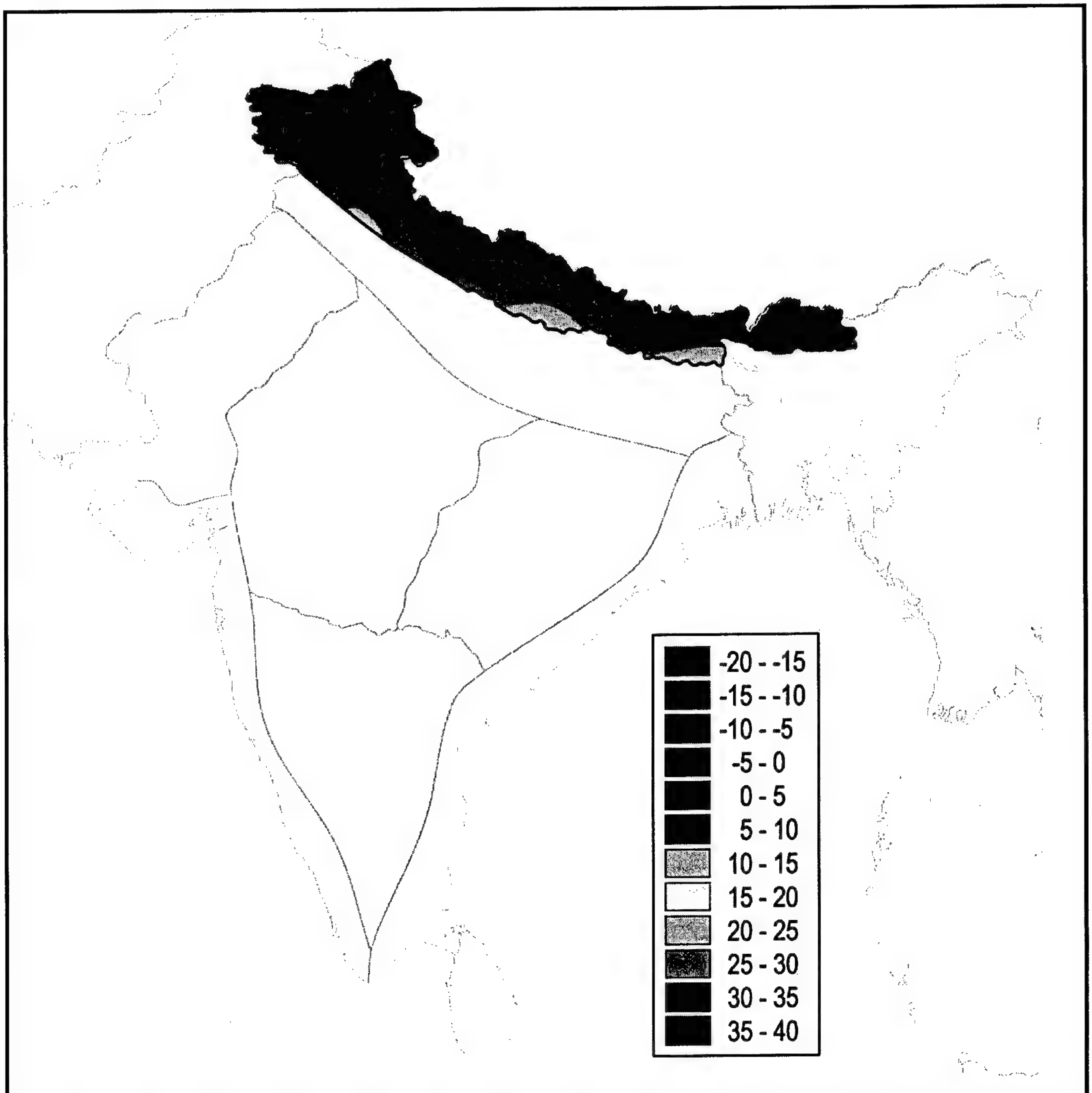


Figure 7-10. January Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for January. Daily low temperatures are often higher than the mean. Mean minimum temperatures during other winter season months may be lower or higher, especially at the beginning and ending of the season.

Hot Season

General Weather. This is when prevailing westerlies of winter give way to easterlies of summer. It is also when the large-scale anticyclonic flow associated with the Asiatic high weakens, disappears, and is eventually replaced by the Asiatic thermal low. As the North Pacific high and the subtropical ridge move north, the STJ shifts north of the region. The beginning of the season is marked by prevailing westerlies across the entire region, soon followed by a transition that brings easterlies to Bhutan and Sikkim. The easterlies migrate westward as the season progresses. The progression of the easterlies periodically slows or surges because of perturbations in the prevailing flow. Cloudiness and precipitation begin to increase in the east and decrease across the west. While most of the subcontinent records the hottest temperatures of the year in this season, the term "hot season" is a misnomer for most of the Himalayas. Only a few stations record their warmest mean high or extreme high temperatures during this season. Most sites record their highest temperatures later, during June or July.

Sky Cover. Figure 7-11 shows occurrence rates of ceilings below 5,000 feet at representative stations. Early in the season, there is a gradual reduction in ceilings below 5,000 feet. As the STJ moves north of the area, the prevailing westerlies weaken and bring fewer migratory systems through the region. The improvement in conditions is spurred by the retreat of the westerlies, rather than the transition to easterlies. This lasts until the easterlies reach the affected area. Across Bhutan and Sikkim, the improvement is brief; it lasts until late March. The improvement continues at Kathmandu and eastern Nepal until early May, when low ceilings begin to increase again. Improvement lasts until late May from Surkhet to Dehra Dun. It continues well into the southwest monsoon for most of Kashmir and the western Himalayas.

In March, Darjeeling records the lowest amount of ceilings below 5,000 feet for any month of the year. Darjeeling records low ceilings 28 percent of the mornings and 49 percent of the afternoons in March. A slight worsening is reflected in April, and by May, Darjeeling records ceilings below 5,000 feet 66 percent of the time. In March and April, Kathmandu records ceilings below 5,000 feet 10 percent of the time in the afternoons. By May, they increase to 20 percent of the time in the afternoons. Farther west, Surkhet and Bhairawa record ceilings below 5,000 feet less than 10 percent of the time. West-central Nepal most consistently records the fewest low ceilings. The area is far enough east that prevailing westerlies of winter quickly retreat and leave the area unaffected by migratory systems and far enough west the easterlies do not usually arrive until late May. The area from Uttar Pradesh to Kashmir is far enough west that it still feels the lingering effects from the prevailing westerlies. The farther west the location, the longer it is affected by the westerlies. Srinagar is far enough west that ceilings below 5,000 feet occur 30-40 percent of the time in April, but a gradual decrease over the entire season is distinct. The easterlies do not usually get to Srinagar until after the end of the season.

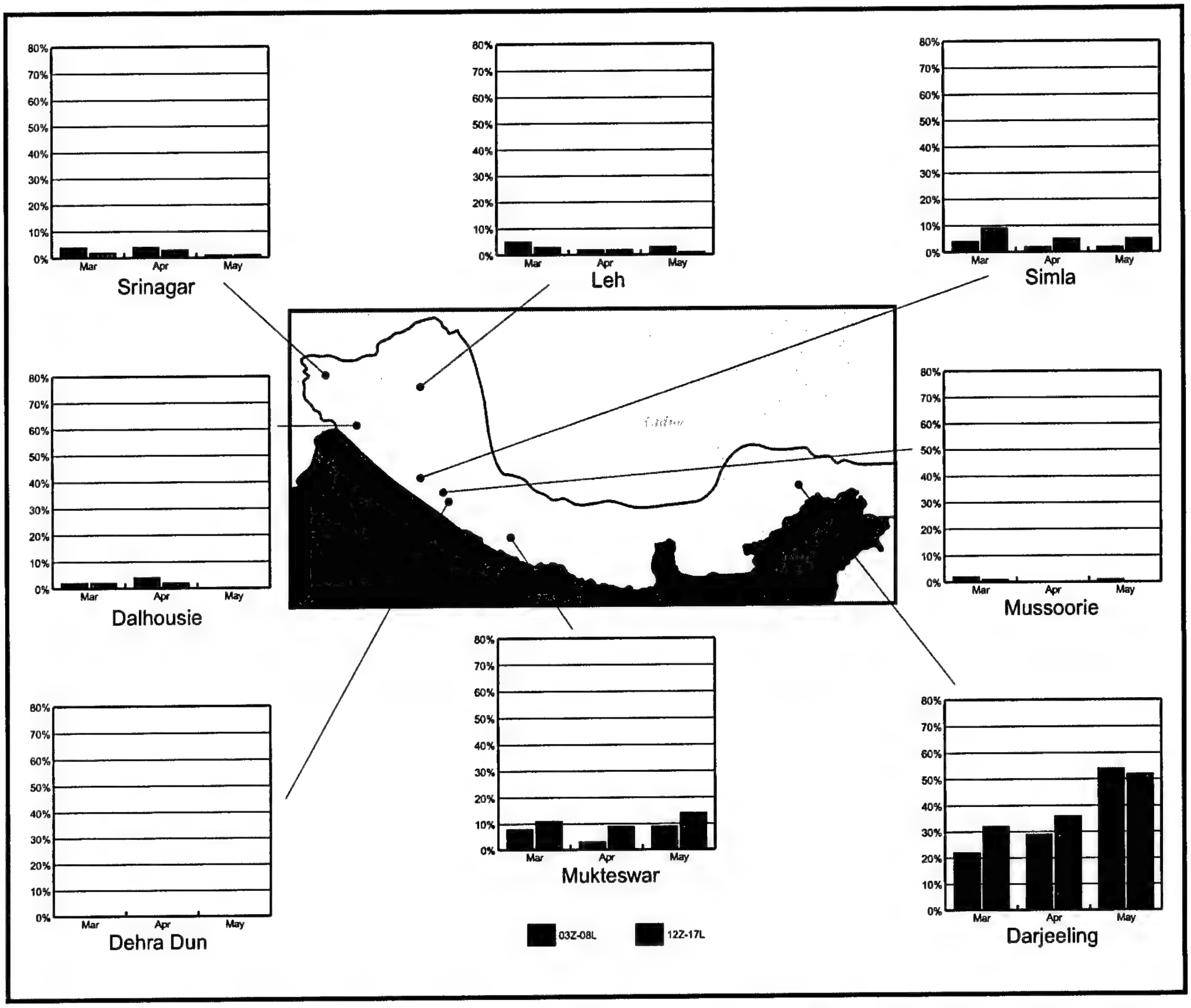


Figure 7-11. Hot Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Darjeeling averages visibility less than 2 ½ miles (4,000 meters) 50-60 percent of the time and records reduced visibility more than any station in the region. The approaching easterlies bring a moisture influx into the eastern Himalayas from the Bay of Bengal. The inversion that traps fog and atmospheric pollutants in Kathmandu valley is still present during the hot season, but is not nearly as strong as during winter. Kathmandu experiences visibility under 3 miles (4,800 meters) 68 percent of the mornings in March and 28 percent of the mornings in May. The fog quickly dissipates by late morning as soon as the inversion breaks. Afternoons at Kathmandu have visibility under 4,800 meters less than 5 percent of the time. Excellent visibility is experienced from Surkhet westward through Dalhousie. Each location in this region of the western Himalayas averages visibility under 4,800 meters less than 5 percent of the time. Weaker westerlies bring fewer migratory systems and fewer fog episodes to the region. Although visibility across northern Kashmir is usually poor, it improves as the season progresses. Srinagar has visibility under 4,000 meters 27 percent of the time in March and 11 percent of the time in May. Srinagar, Dras, and Leh are far enough north they experience effects of the retreating westerlies, especially at the beginning of the season. Figure 7-12 shows regional occurrence rates of visbility below 4,000 meters at representative stations.

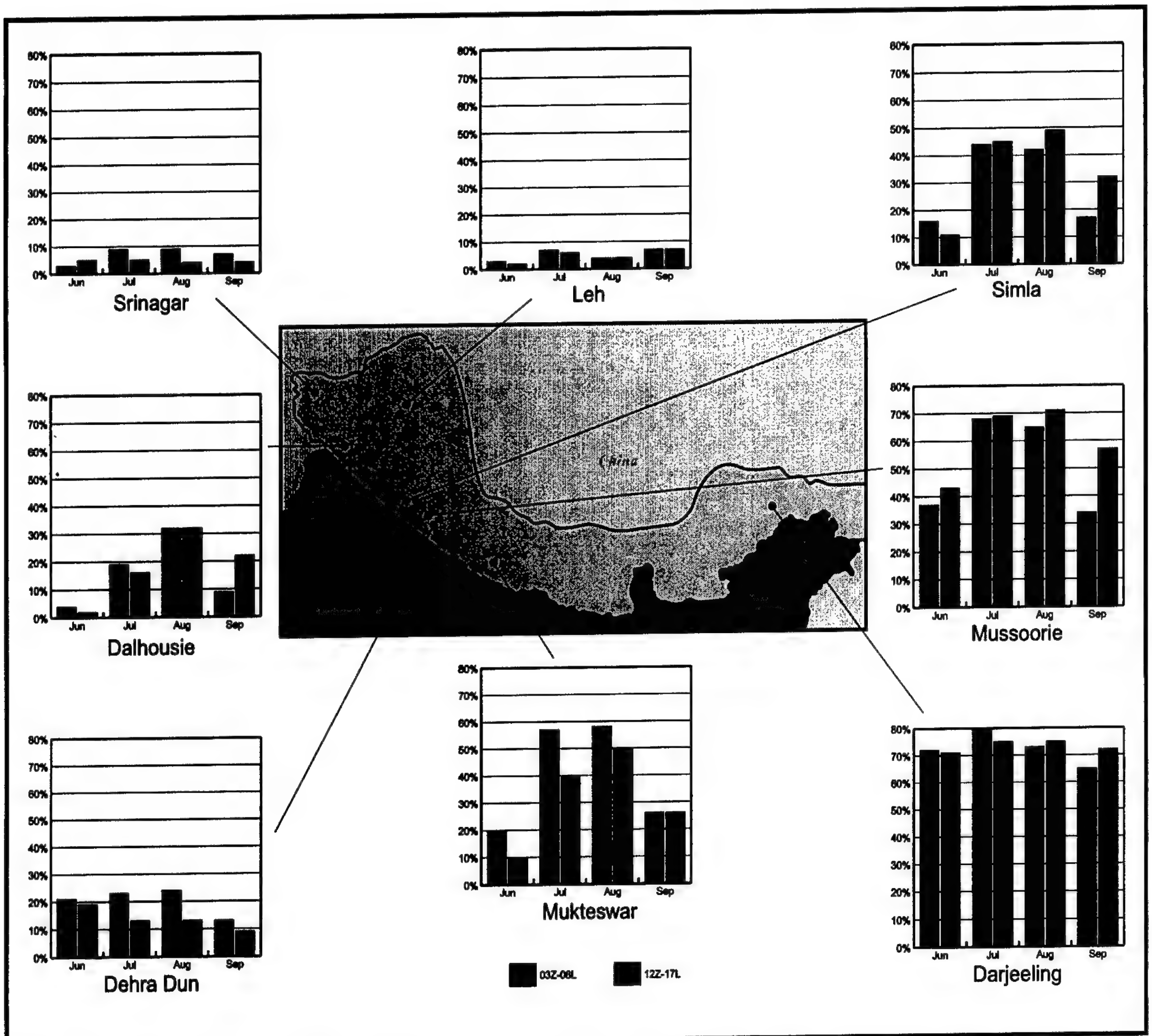


Figure 7-12. Hot Season Percent Frequency of Visibility below 21/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. The large-scale wind patterns transition from the westerlies of winter to the easterlies of the southwest monsoon, however, any small-scale changes are overwhelmed by terrain effects. The STJ moves northward through the region and brings strong westerly winds to locations that have a canyon or mountain pass west of the site. Surkhet continues to have steady northerly drainage winds at night and enhanced westerly winds in the afternoon after the inversion breaks. During afternoons, the wind is rarely calm at Surkhet. April, the windiest month, is when Surkhet has westerly winds of 8-17 knots 10 percent of the time. Afternoon southwesterlies and westerlies are funneled into Kathmandu after the inversion breaks. Winds of 8-17 knots are recorded at Kathmandu nearly 50 percent of the time. These winds are most apparent during March and April, and begin to weaken in May. There is no strong easterly wind at Kathmandu. See Figure 7-13 for surface wind roses at representative sites within the region.

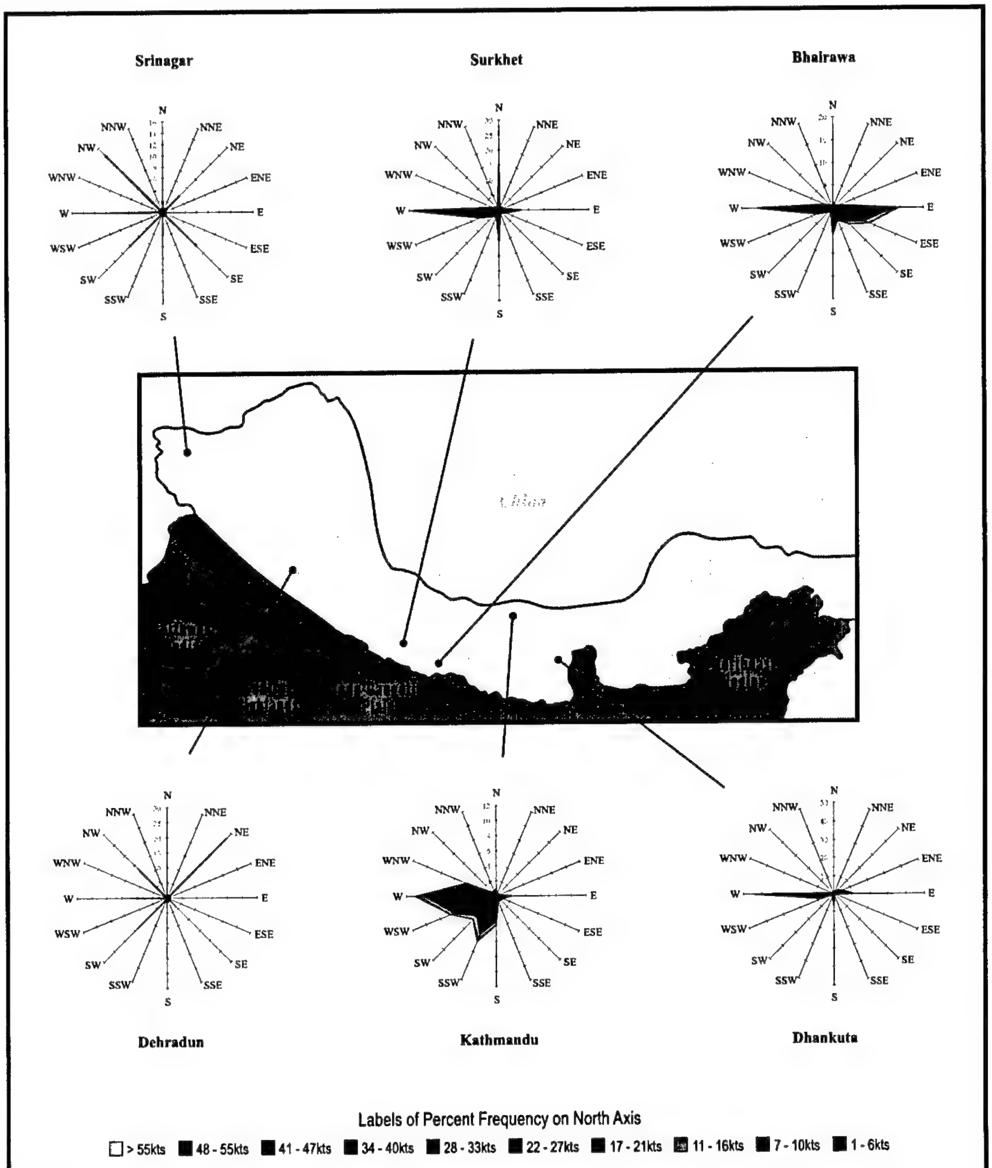


Figure 7-13. April Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Level Winds. In March, as the STJ weakens and starts to shift poleward, it extends from north-central Kashmir to southern Tibet. The highest mean jet winds of the year are experienced at Srinagar in March. While the actual speeds are slightly lower than during winter, the jet core is directly over Srinagar. The STJ is best represented at 200 mb as a band of 75-100 knot winds in March. By May, the jet is far north of the region, and only extreme northern Kashmir experiences 50-knot winds at 200 mb. Depending on the elevation of a location, both friction and other terrain effects influence the wind speed and direction for nearly every upper-level pressure surface from 850 mb to 400 mb. Figure 7-14 shows upper-air wind roses over Srinagar, India.

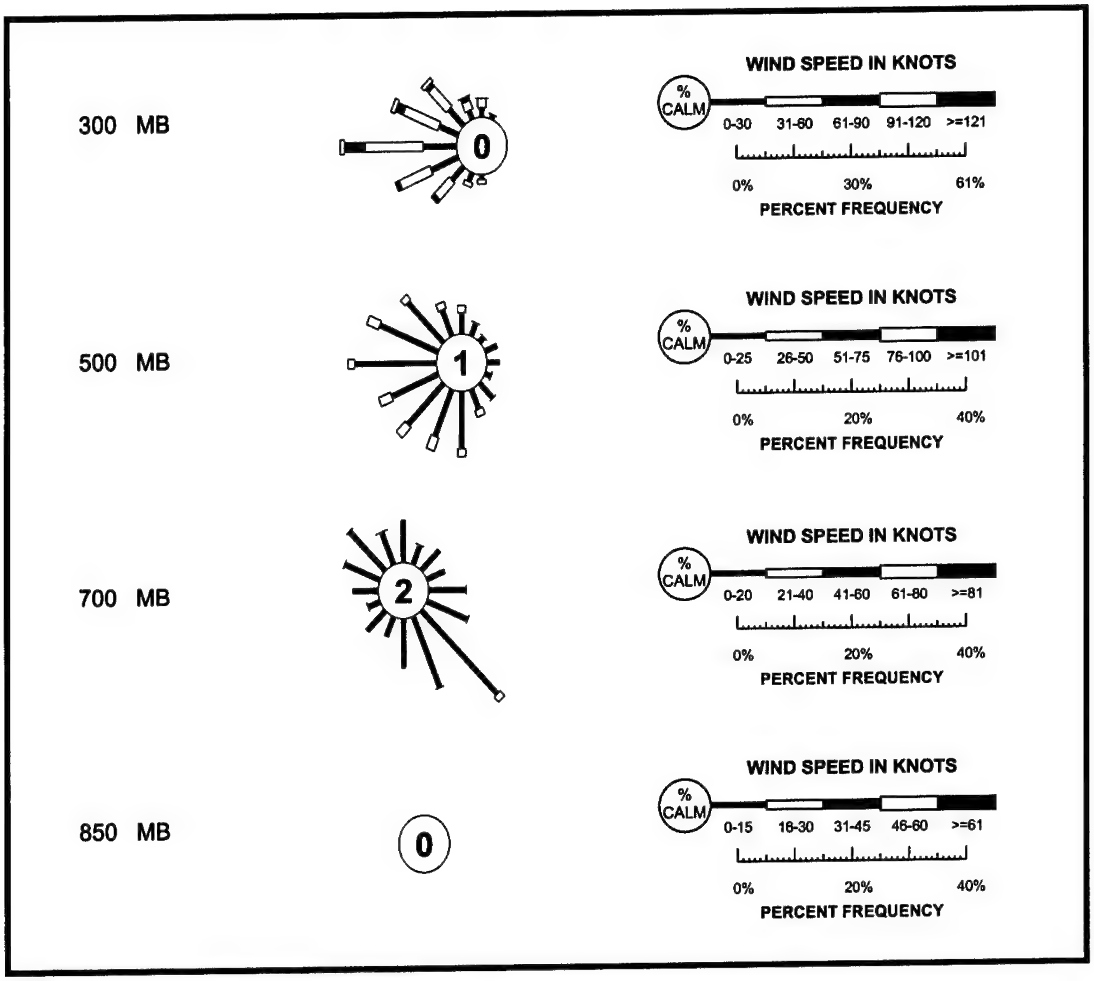


Figure 7-14. April Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb over Srinagar, India.

Precipitation. Migratory systems continue to bring copious precipitation to the northwestern Himalayas. The Himalayas north and east of Srinagar record more than 12 inches (305 mm) of precipitation in March. As the westerlies weaken and shift north, the total precipitation in this stretch of the Himalayas decreases. The area records 8 inches (203 mm) in April and only 4 inches (102 mm) in May. The Pir Panjal Mountains south and west of Srinagar get the most precipitation in March, 6 inches (152 mm), and the least in May, 2-3 inches (51-76 mm). Between these two moist ranges, the Vale of Kashmir is comparatively dry. This valley records about 3 inches (76 mm) per month all season. Farthest inland, the crests of the Ladakh Mountains record about 2-3 inches (51-76 mm) of precipitation each month.

The area of greatest precipitation shifts from the western Himalayas to southeastern Bhutan. As the easterlies begin to affect the eastern section of the region, precipitation totals increase dramatically along the southern slopes of the Bhutanese Siwaliks. Across this area, totals jump to over 4 inches (102 mm) in March and 8 inches (203 mm) in April. By May, the easterlies are near their peak, and this area of southeastern Bhutan records 16 inches (406 mm) of precipitation. Across Sikkim, totals increase from 3-4 inches (76-102 mm) in March to over 12 inches (305 mm) in May.
The increase in precipitation is not as drastic at Kathmandu and across east-central Nepal. Totals in this area increase from 2 inches (51 mm) in March to 3-4 inches (76-102 mm) in May. Across western Nepal, Uttar Pradesh, and Himachal Pradesh, there is little change from late winter precipitation totals to those late in the hot season. Totals of 2 inches (51 mm) per month occur across this zone all season.

The driest areas of the region are on the lee side of the great ranges. The Indus River valley near Leh is in the rain shadow of the northwestern Himalayas and records less than one inch (25 mm) for the entire season. The river is fed by countless mountain streams. Another extremely dry section is in the lee of the Ladakh Mountains in far northern Kashmir. This region also records less than one inch (25 mm) for the entire hot season. Most of the China-Nepal border north of the Himalayas also records little more than one inch (25 mm) per month all season. Figure 7-15 shows the mean precipitation amounts across the region in April. Figure 7-16 shows the mean seasonal days with precipitation and thunderstorms for locations around the region.

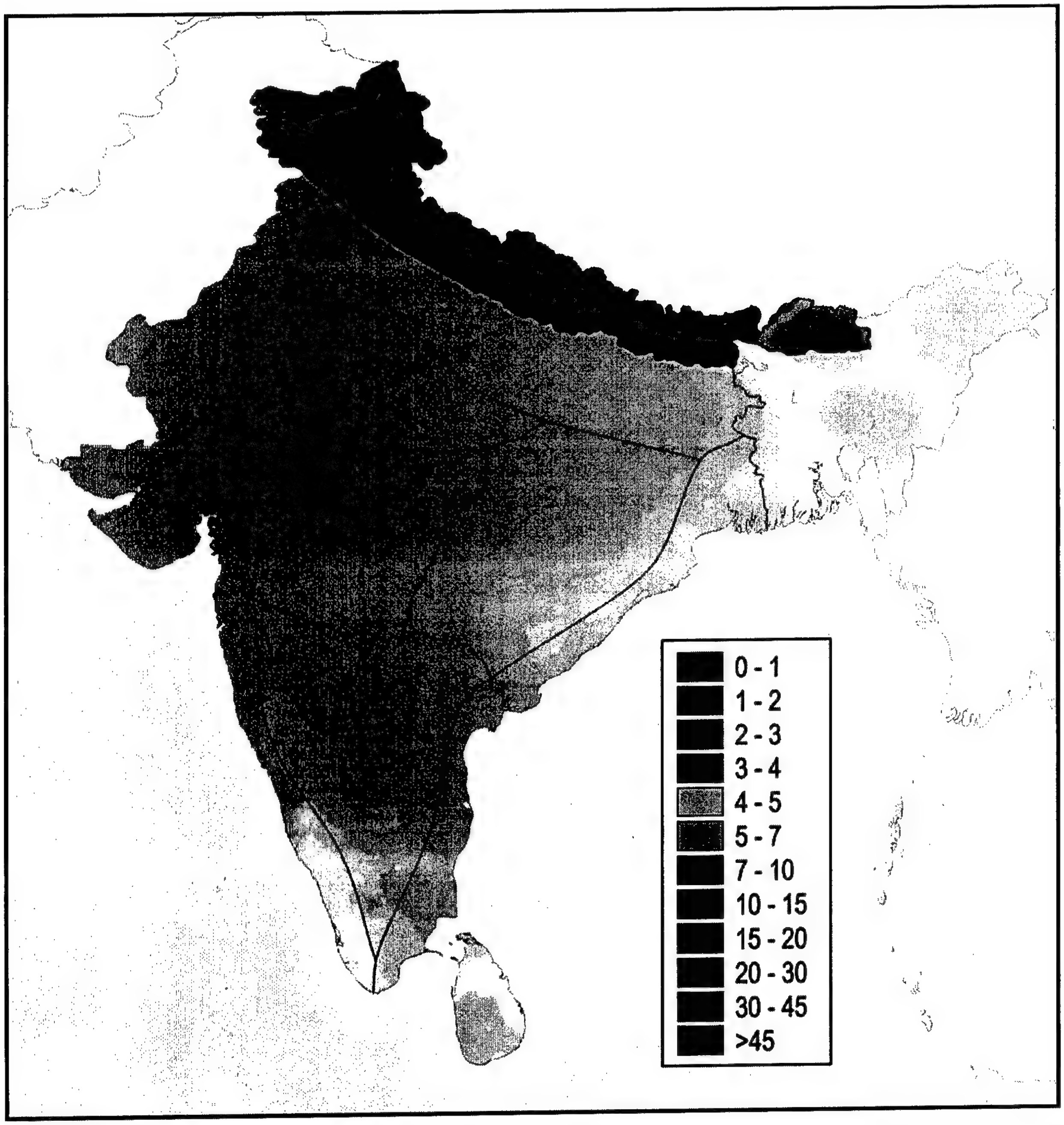


Figure 7-15. April Mean Precipitation (Inches). The isopleths depict the mean precipitation totals received during the most representative month of the hot season.

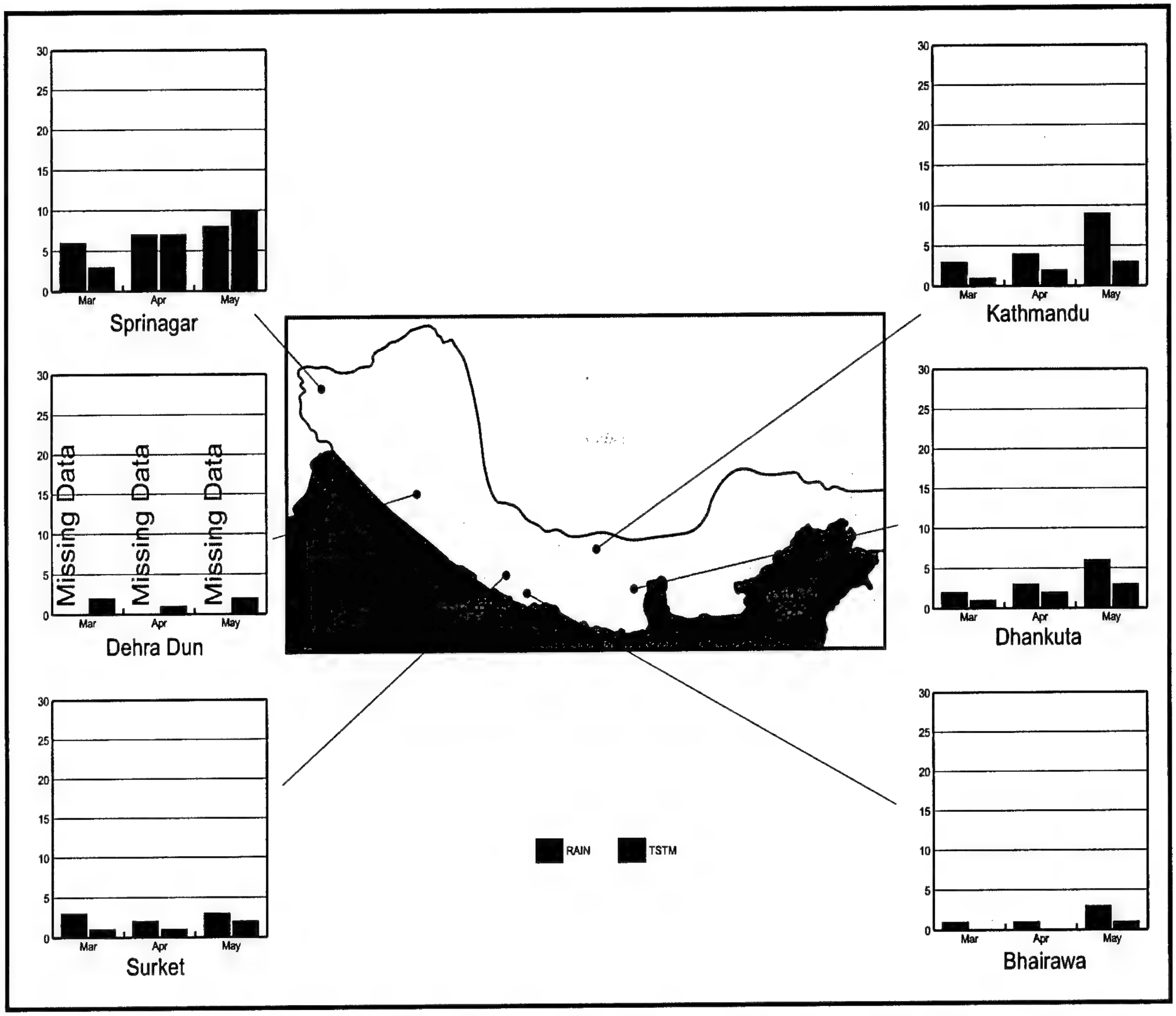


Figure 7-16. Hot Season Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures. Temperatures are closely related to site elevation and latitude. The warmest temperatures are recorded at lower elevations in the Siwaliks. Cooler temperatures are recorded at higher elevations. In most of India, the warmest temperatures of the year occur in this season, but in the Himalayas, the annual warmest mean temperatures are delayed into the southwest monsoon. Only a few stations in the Siwaliks across northern Himachal and Uttar Pradesh record their highest annual mean highs in this season. Dehra Dun, Mukteswar, and Mussoorie record their warmest mean highs during May. The warmest mean highs at any station in the region are recorded at Dehra Dun during May (96°F or 36°C). Hot, arid cyclonic flow from the Asiatic low brings the warmest temperatures of the year to this area in the weeks immediately before the southwest monsoon arrives.

The month-to-month range of mean highs is defined by available atmospheric moisture and how far west the easterlies have encroached. Across Kashmir, mean highs rapidly increase an average of 24 Fahrenheit (13 Celsius) degrees from March to May. To the east, across Himachal and Uttar Pradesh, the change is much less dramatic, only about 17 Fahrenheit (10 Celsius) degrees. The range of seasonal mean high temperatures changes decreases across eastern Nepal, Sikkim, and Bhutan. At Kathmandu, the mean highs range from 77°F (25°C) in March to 85°F (29°C) in May. Darjeeling has an even smaller range, from 56°F (13°C) in March to 65°F (18°C) in May. The temperature range is similar at Thimphu. The Bhutanese capital has mean highs that range from 67°F (19°C) in March to 75°F (24°C) in May.

Mean lows ranges are also closely related to the continentality of a location. The coldest location, Dras, has mean lows from 4°F (-16°C) in March to 34°F (1°C) in May. While Leh is farther inland, Dras is in the rain shadow of the Himalayas. Leh is on the windward side of the Ladakh Mountains and receives much more precipitation. Consequently, mean lows at Leh only range from 21°F (-6°C) in March to 37°F (3°C) in May. Farther east, the encroachment of the easterlies also defines the range of month-to-month mean low temperatures. At Dehra Dun, the mean lows range from 54°F (12°C) in March to 70°F (21°C) in May. Mean lows at Kathmandu range from 45°F (7°C) in March to 60°F (16°C) in May. At the wettest location, Darjeeling, mean lows range from 43°F (6°C) in March to 52°F (11°C) in May. Thimphu has mean lows that range from 49°F (9°C) in March to 57°F (14°C) in May. Even though there are other locations in northern Kashmir that record heavier precipitation totals than Darjeeling or Thimphu, the effect of the easterlies is greater across Sikkim and Bhutan. See Figures 7-17 and 7-18 for April mean highs and lows, respectively.

Only a few stations record their extreme highs in this season. The extreme highs at Dalhousie, Simla, and Mussoorie occurred in May. All three recorded an extreme high in the range from 89°F (32°C) to 94°F (34°C). All three also recorded nearly the same temperatures in June; however, the extreme high that stands apart is 111°F (44°C) recorded at Kathmandu. This extreme high is at least 11 Fahrenheit (6 Celsius) degrees above that of any other month and can probably be attributed to an extremely hot, dry foehn wind. There were probably drought conditions at Kathmandu when a strong, late-season westerly migratory system came through and produced an intense foehn wind that resulted in a rapid temperature increase.

The coldest extreme low was -29°F (-34°C) at Dras in March. The range of extreme lows at Dras varies by 39 Fahrenheit (22 Celsius) degrees between March and May. In contrast, Leh has a range of only 21 Fahrenheit (11 Celsius) degrees between March (-3°F or -19°C) and May (18°F or -8°C). Extreme lows only vary by 15 Fahrenheit (8 Celsius) degrees at Kathmandu and 9 Fahrenheit (5 Celsius) degrees at Darjeeling. The extreme lows at Kathmandu range from 34°F (1°C) in March to 49°F (9°C) in May. Darjeeling's extreme lows range from 30°F (-1°C) in March to 39°F (4°C) in May.

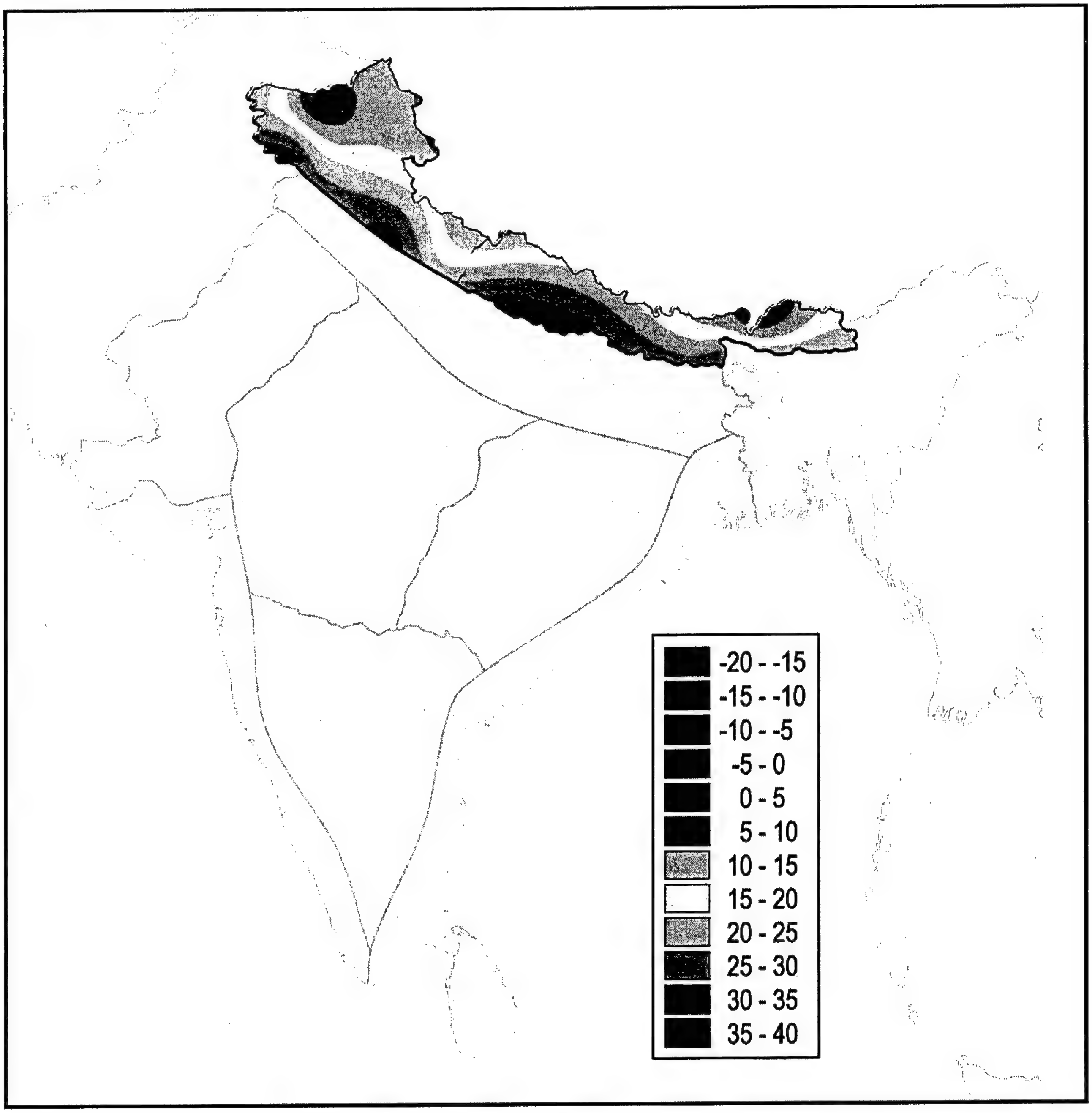


Figure 7-17. April Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for April. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

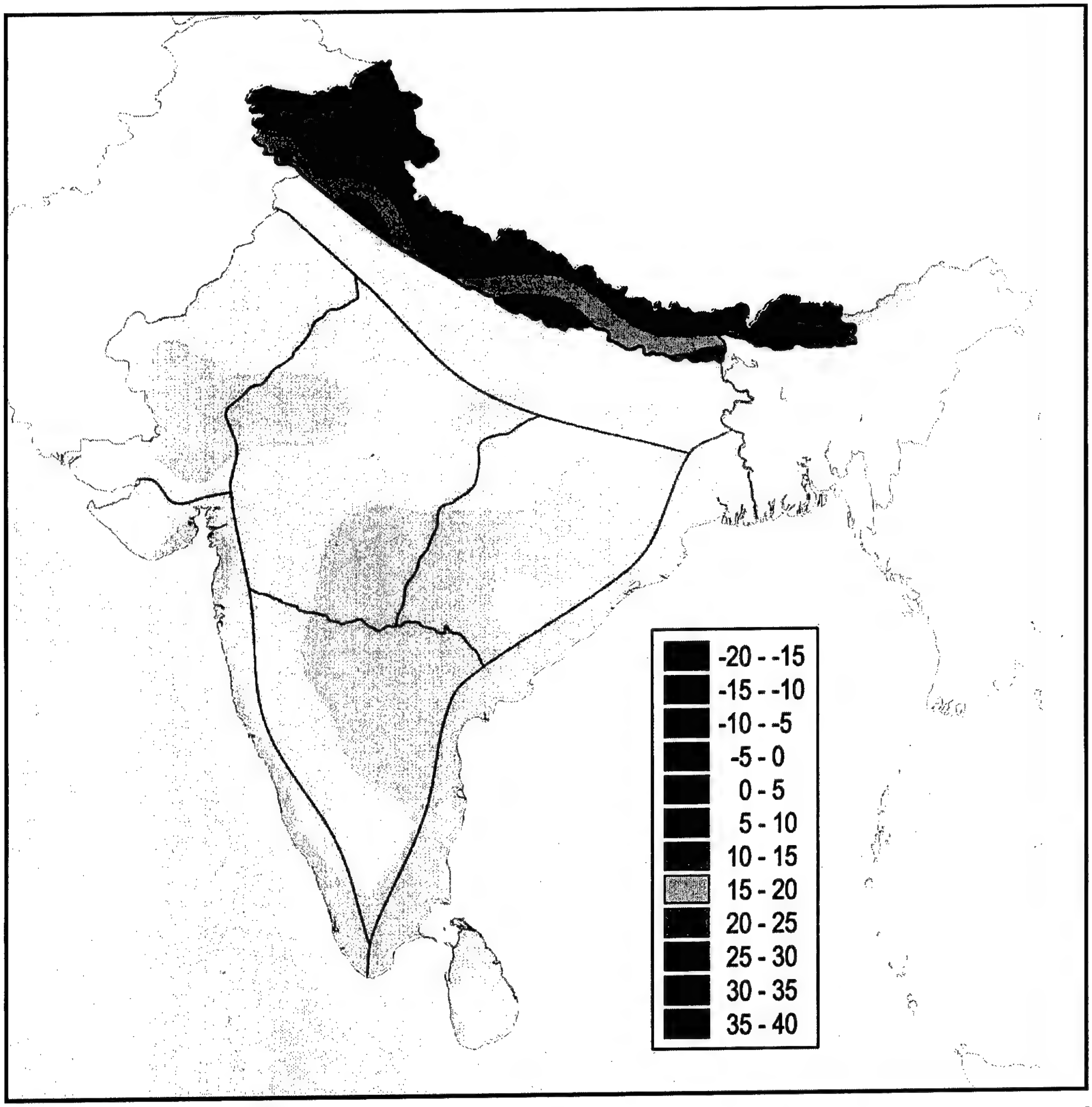


Figure 7-18. April Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for April. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other hot season months may be lower or higher, especially at the beginning and ending of the season.

Southwest Monsoon

General Weather. At the start of the season, the Asiatic low is firmly entrenched over Pakistan as an anchor for the equatorial trough (ET). The Tibetan upper-level anticyclone is in place over southern Tibet and brings moist, easterly winds to the Himalayas. The southwest monsoon begins in the eastern part of the region and progresses westward. Across Bhutan and Sikkim, the monsoon normally begins by the first week of June. By the second week of June, the monsoon reaches as far west as central Nepal. The entire region is under the influence of the southwest monsoon by early July. The southwest monsoon starts to fade as soon as it begins in the westernmost areas. The actual rainy period is quite short at the far northern edge of its sphere of influence.

Through most of the season, the ET extends east from the Asiatic low along a line just south of the Himalayas. This usually brings the heaviest precipitation to the Siwaliks and the foothills across northern India. Perturbations in the Asiatic low cause ripples along the ET. These minor impulses cause the ET to move northward into the Himalayas and cause brief episodes of heavy rainfall. Periodically, a 2-3 day break in the monsoon over central India is caused by a fair-weather induced anticyclone. This forces the ET northward and results in extremely heavy precipitation across the Himalayas.

By early September, the Asiatic low begins to weaken and fill. Without a strong anchor, the ET rapidly retreats equatorward. Additionally, the Tibetan upper-level high breaks down and rapidly moves southeastward. The STJ slips south and returns to northern Kashmir. The easterlies rapidly disappear and are replaced by the prevailing westerlies.

Sky Cover. The arrival of the southwest monsoon brings a dramatic increase in cloud cover. Between June and August, ceilings below 5,000 feet occur at Darjeeling 80-85 percent of the time. In September, when the monsoon withdraws, the rates drop to 70-75 percent of the time. Kathmandu records ceilings below 3,000 feet 25 percent of the time in the early mornings and late afternoons of June and September, and 35 percent of the same times in July and August. During the early mornings, nighttime stratus is trapped beneath the inversion. From July to September, this morning stratus forms a ceiling below 1,000 feet 20 percent of the time. By late morning, the inversion breaks and the stratus disappears. Ceilings below 3,000 feet occur in the late morning less than 10 percent of the time, however by mid-afternoon, cumulus clouds form over the nearby mountains and create a ceiling 35 percent of the time. After sunset, the clouds collapse and spread to form stratocumulus and stratus.

Since the southwest monsoon arrives across western Nepal later than across eastern Nepal, the amount of time ceilings occur below 3,000 feet at Surkhet is higher in August than during June or July. Ceilings below 3,000 feet occur 46 percent of the time in July and 55 percent of the time in August. Even though Dehra Dun and Mussoorie are less than 6 miles (10 km) apart, Mussoorie records ceilings below 5,000 feet nearly twice as often as Dehra Dun. During July and August, Mussoorie records ceilings below 5,000 feet 80-90 percent of the time while Dehra Dun records them 30-45 percent of the time. The reason for the disparity is Mussoorie is more than 5,000 feet (1,500 meters) higher than Dehra Dun. August is the only southwest monsoon month when ceilings below 5,000 feet occur more than 30 percent of the time at Srinagar because Kashmir is where the southwest monsoon arrives last and leaves first. Moisture from the southwest monsoon rarely reaches Leh and Dras. Both are blocked by the Himalayas and receive low ceilings less than 10 percent of the time all season. Figure 7-19 shows occurrence rates of ceilings below 5,000 feet at representative stations.

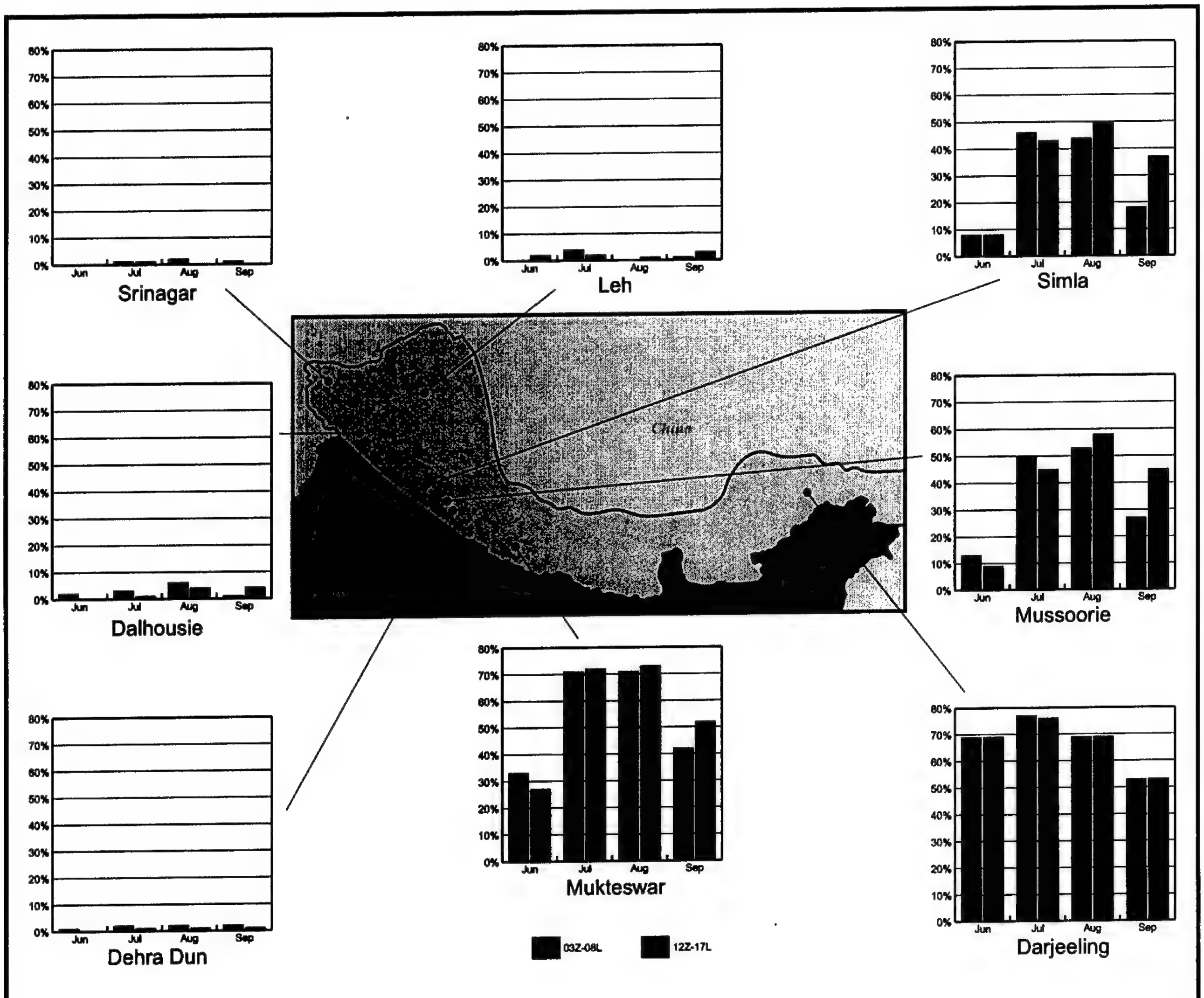


Figure 7-19. Southwest Monsoon Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. Visibility is primarily restricted by prolonged precipitation and by nocturnal fog and stratus. The periods with the highest rate of reduced visibility usually coincide with the time when the heaviest precipitation is recorded at any given location. For locations in the eastern one-third of the region, this is usually in July. Farther west, across western Nepal, Uttar and Himachal Pradesh, it most often in July and August. Poor visibility across Kashmir is recorded most in August. Unless otherwise noted, the high value expressed in a range of values in the paragraphs that follow is for the morning and the low number is for the afternoon.

Darjeeling records visibility reduced below 2 ½ miles (4,000 meters) more in July than during any other month of the year. Visibility drops below 4,000 meters at Darjeeling 75-80 percent of the time; it drops below 1 1/4 miles (2,000 meters) 70-75 percent of the time. Visibility is slightly worse in the mornings in fog and stratus. At Kathmandu, this is the time of year with the best visibility. The strong radiational inversion that caps the Kathmandu valley and traps stagnant air in the winter is absent. From June-August, the visibility is below 4,000 meters less than 5 percent of the time. In September, the inversion returns and the incidence of poor visibility increases to 25 percent of the September mornings at Kathmandu. This fog quickly dissipates by late morning, and the visibility quickly improves in the afternoon.

From Surkhet to Dehra Dun, the visibility is worst in July and August. Surkhet has visibility below 4,000 meters 15-20 percent of the time, mostly in the morning. In the afternoon, it occurs less than 5 percent of the time. At Mukteswar, visibility is slightly worse in August than in July. Visibility below 4,000 meters occurs 40-57 percent of the time in July and 50-58 percent of the time in August. After the southwest monsoon retreats in September, visibility drops below 4,000 meters 26 percent of the time. Visibility below 2,000 meters at Mukteswar occurs nearly as often in July (37-54 percent of the time) and August (47-55 percent of the time). Farther west, the incidence of reduced visibility decreases reaches an abrupt maximum in August. Since the southwest monsoon spends the shortest time in Kashmir, visibility quickly improves in September. At Dalhousie, visibility drops below 4,000 meters 32 percent of the time in August. Moisture from the southwest monsoon rarely encroaches into northern Kashmir or north of the Himalayas. Srinagar and Leh have visibility below 4,000 meters less than 10 percent of the time. Figure 7-20 shows occurrence rates of visibility below 4,000 meters at various representative regional stations.

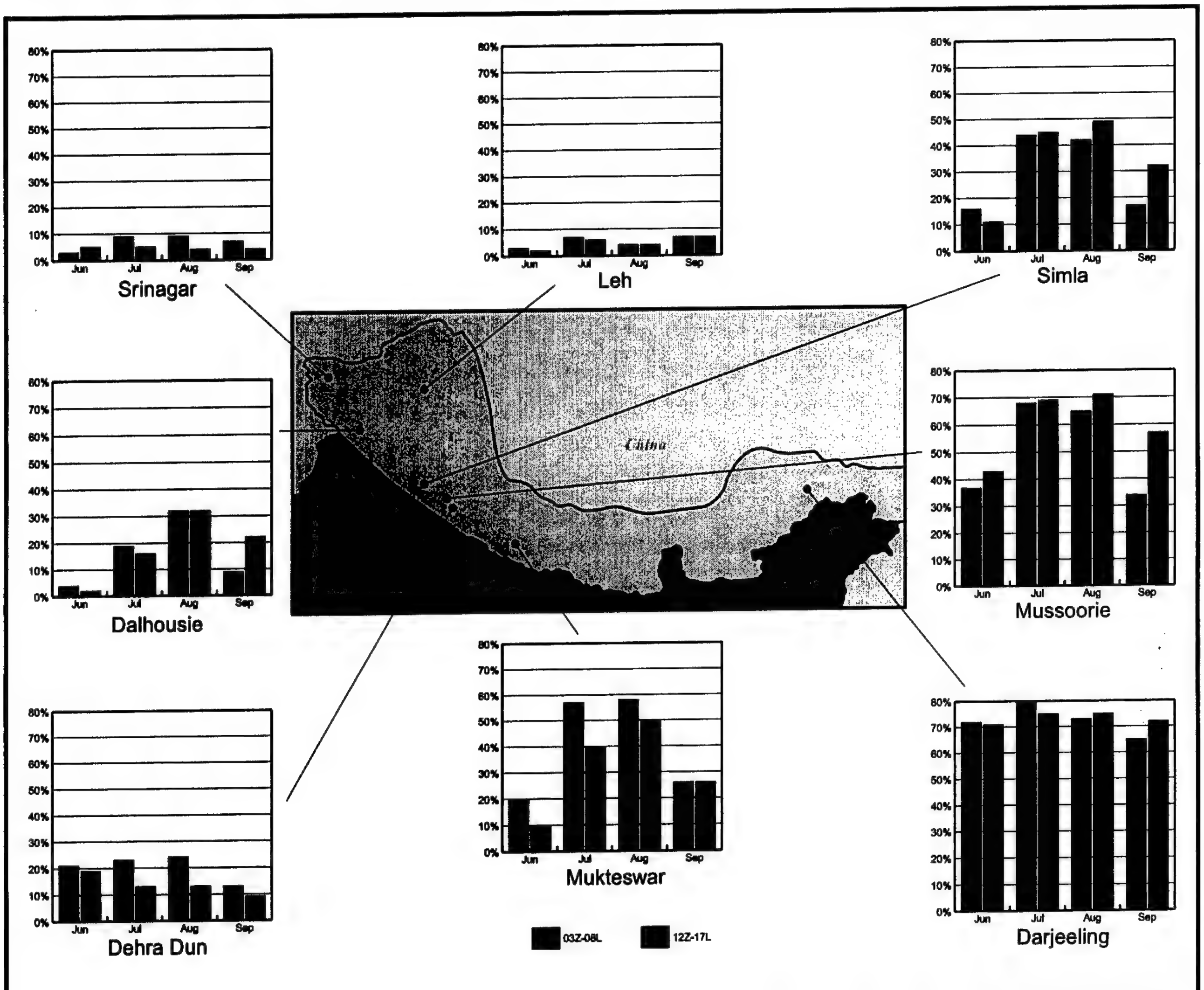


Figure 7-20. Southwest Monsoon Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Surface winds are dominated by terrain. Nearly every location is susceptible to channeling, venturi winds, foehns, and localized mountain/valley winds. The predominate flow is easterly, and when the terrain is oriented east-west, it tends to augment the prevailing flow. When the terrain is oriented north-south, the terrain determines the local winds, no matter how strong the prevailing flow. Bhairawa has the most discernible easterly flow of any location in the region. From June-September, east winds are nearly constant at all hours. Speeds of 9-17 knots occur 25-30 percent of the time. The inversion at Kathmandu is at its weakest of any time during the year, but it is still strong enough to prevent the low-level jet from affecting the city at night. Calm conditions invariably last throughout the night. All season, Kathmandu averages calm winds at least 95 percent of the time. By late morning, the inversion breaks and a steady, southwest wind blows throughout the afternoon. Wind speeds of 9-17 knots occur 30-40 percent of the time. As soon as the sun sets, the inversion sets up again and the winds go calm again. See Figure 7-21 for surface wind roses at representative sites.

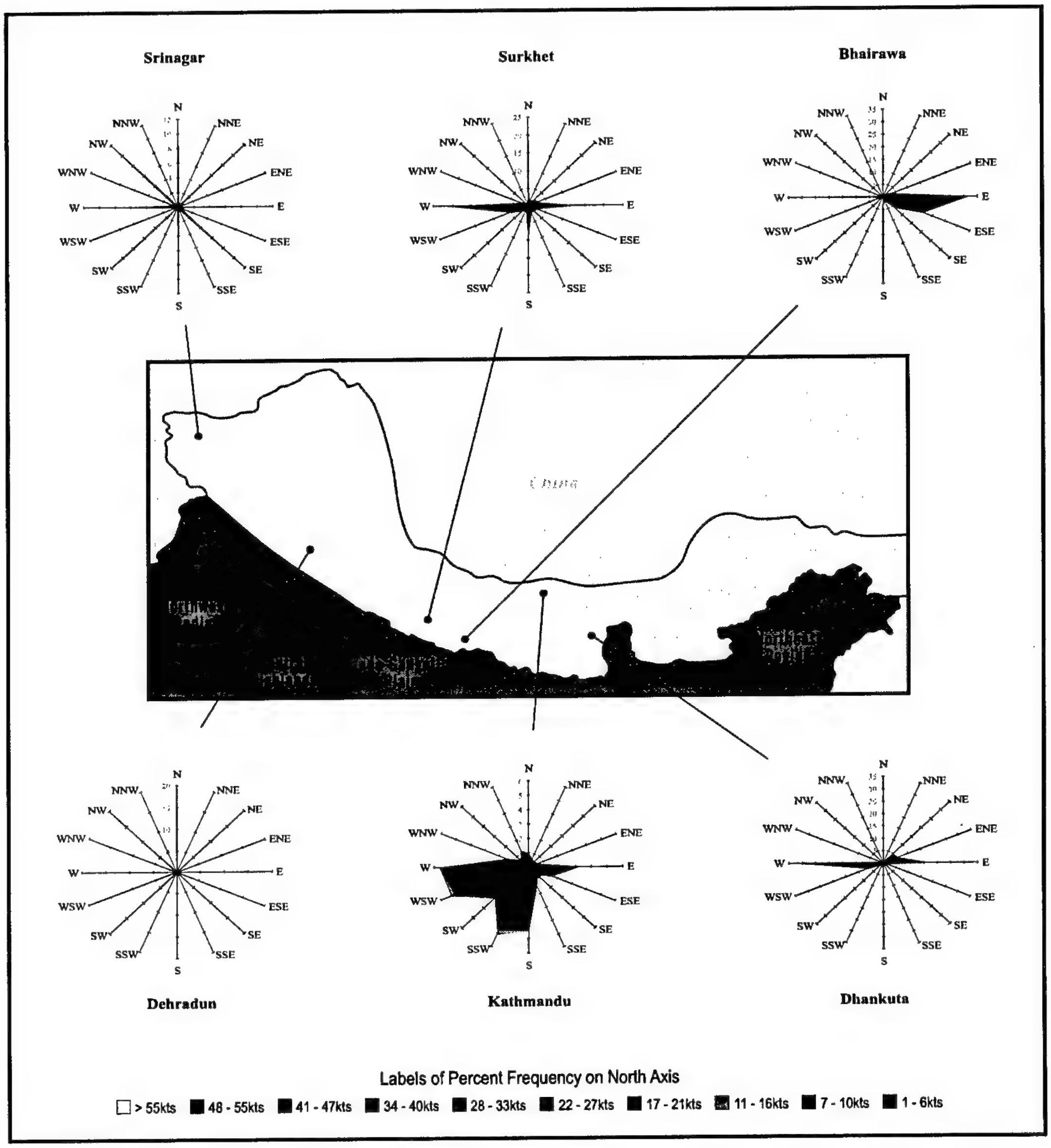


Figure 7-21. July Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Level Winds. In June, the main core of the STJ moves north of northern Kashmir. It remains far north of the region until mid-September. During June, the jet is only detected at 200 mb as a weak band of 50-knot westerlies over Srinagar. Farther east, the jet-level winds become variable over western Nepal and weak (less than 20 knots) easterly over eastern Nepal, Sikkim, and Bhutan. Over the Himalayas, even the 300-mb winds are affected by terrain. Along the northern edge of the eastern half of the region, wind speeds are lower and directions more variable than along the southern rim of the area. The northern edge is closer to the core of the Tibetan upper-level anticyclone and consequently, has slower wind speeds. Additionally, the wind direction is more variable because it is directly over the highest mountains. Frictional effects at lower levels are transported upwards over the highest mountain chain in the world. Towards the end of the southwest monsoon, the STJ reenters northern Kashmir and the Tibetan upper-level anticyclone breaks down. The small zone of Kashmir affected by westerlies grows and spreads east. By the end of September, the main jet core (50-75 knots) is over northern Kashmir and weak westerlies affect the western half of the region. The eastern half of the region remains under variable upper-level flow until the post-monsoon season. See Figure 7-22 for wind roses at Srinagar, India.

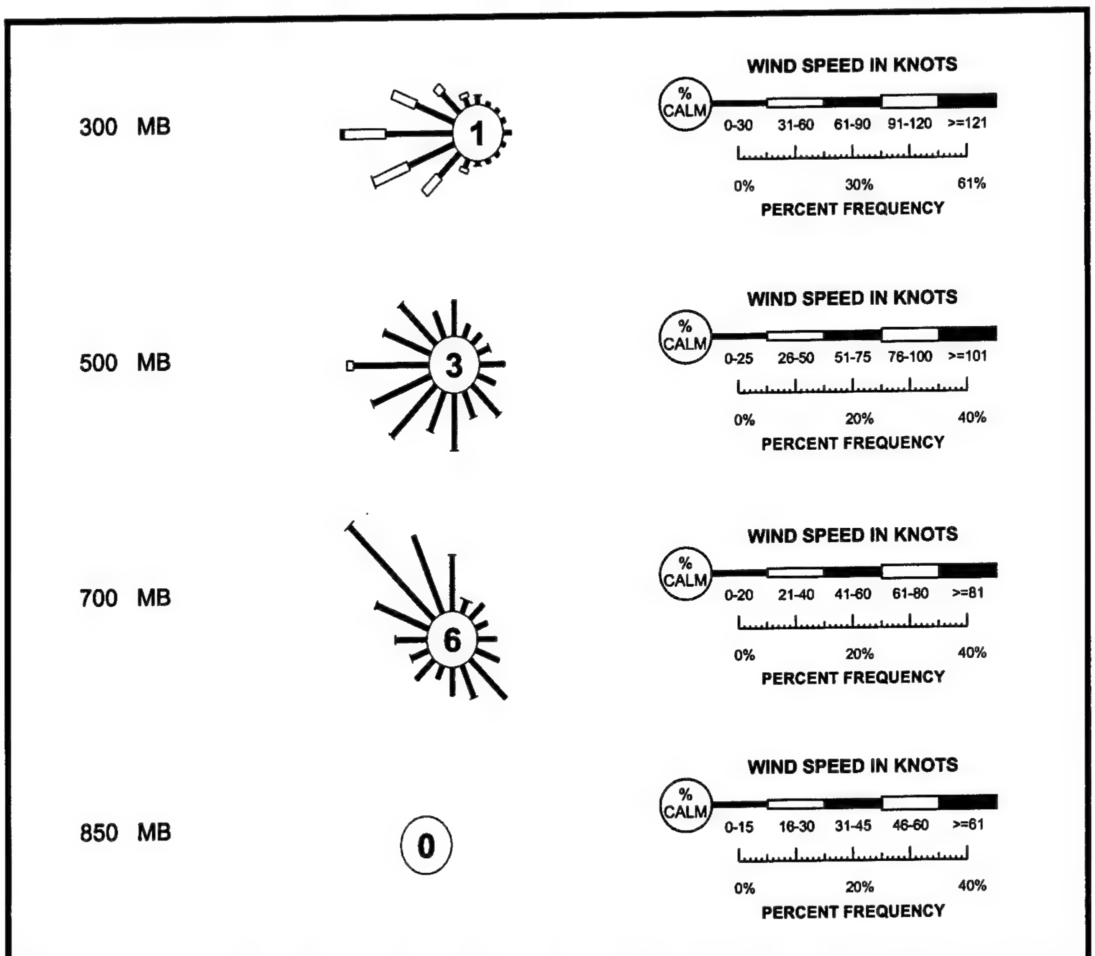


Figure 7-22. July Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb over Srinagar, India.

Precipitation. See Figure 7-23. Across the entire region, there are not only a strong north-south oriented, precipitation-gradient rain shadows, there are also areas of decreased precipitation in the major river valleys of the Nepalese Himalayas. A precipitation trough is an area where precipitation totals are significantly lower than in the mountains on either side of the river valley. These precipitation troughs are formed on the western (lee) slopes of higher terrain. Precipitation troughs are most noticeable in the Arun, Kali, and Karnali River valleys of Nepal. On average, precipitation totals are 4-8 inches (102-203 mm) lower in these river valleys than in the nearby mountains.

At the onset of the southwest monsoon, the most precipitation is recorded across the eastern third of the region. In June, the southwest monsoon is in full force and southern Bhutan and Sikkim record 24-32 inches (610-813 mm) of precipitation. Precipitation totals across this area reach an annual maximum in July; some areas average over 36 inches (914 mm). Totals drop the rest of the season. Southern Bhutan and Sikkim record 24-32 inches (635-813 mm) in August and 20-28 inches (508-711 mm) in September. All season, the high terrain of Bhutan and Sikkim creates a steep north-south precipitation gradient. While the south is subjected to an almost nonstop deluge, the north is much drier. Northern Bhutan and Sikkim average 4-12 inches (102-305 mm) for each month of the southwest monsoon.

Precipitation across the rest of the region gradually increases over time with the westward progression of the easterlies. Precipitation peaks in eastern Nepal from mid July to early August. As in Bhutan and Sikkim, the terrain of Nepal creates a steep, north-south precipitation gradient. In June, while the Siwaliks of southern Nepal average 8-16 inches (203-406 mm) of precipitation, the Chinese-Nepalese border receives only 2-8 inches (51-203 mm). In July, totals in the south increase to 20-28 inches (508-711 mm). Totals in the north increase slightly to 4-12 inches (102-305 mm). By August, eastern Nepal averages 20-32 inches (508-813 mm) in the south and 6-16 inches (152-406 mm) in the north. The area around Mt. Everest gets some of the highest precipitation amounts in the region. The southern slopes of this area record over 20 inches (508 mm) of precipitation per month all season.

Western Nepal, Uttar and Himachal Pradesh get the most precipitation of the season in August. Across the Siwaliks of western Nepal and Uttar and Himachal Pradesh, precipitation amounts range from 8-16 inches (203-406 mm) in June to 16-24 inches (406-610 mm) in August. Across the border region, totals range from 2-6 inches (51-152 mm) in June to 6-16 inches (152-406 mm) in August.

Southwest monsoon precipitation totals across Kashmir are not as easily divided. The three primary mountain ranges of Kashmir, the Pir Panjal, the Himalayas, and the Ladakh each have a distinct rain shadow and each successively more interior range receives less precipitation. The Pir Panjal Mountains have totals that range from 3-6 inches (76-152 mm) in June to 16-24 inches (406-610 mm) in August. Because the southwest monsoon withdraws from Kashmir in early September, precipitation totals remain relatively high at 6-12 inches (152-305 mm). Precipitation totals in the Vale of Kashmir and Chandra River valley are drastically lower than in the neighboring Pir Panjal. The Vale averages less than 2 inches (51 mm) for each month of the monsoon season. Not quite as enclosed as the Vale, the Chandra River valley receives slightly more moisture from the southwest monsoon. The Chandra River averages from less than 2 inches (51 mm) or rainfall in June to 3-4 inches (76-102 mm) of rainfall in August.

Precipitation peaks across the Himalayas of Kashmir in July after a June lull. July's totals of 8-12 inches (203-305 mm) are much higher than the June average of 3-4 inches (76-102 mm). As the southwest monsoon retreats in August, totals drop to 4-8 inches (102-203 mm). In September, the prevailing westerlies return to Kashmir and keep the rainfall totals in the Himalayas at 4-8 inches (102-203 mm). The Indus River valley to the west of the Himalayas lies in one of the most significant rain shadows in the world. This valley receives little or no precipitation from the southwest monsoon. Occasionally, several years pass between rains here. In June, the Indus River valley averages less than 0.2 inch (5 mm). Totals for the rest of the season are only slightly higher, 0.2-0.4 inch (5-10 mm). For the entire season, the Indus River valley averages little more than one inch (25 mm) of precipitation. The third, and farthest interior mountain range of Kashmir, the Ladakh Mountains, receives a meager amount of rainfall during the southwest monsoon

season. Not much moisture from the southwest monsoon manages to pass through the Himalayas to the Ladakh. The Ladakh Mountains average 1-2 inches (25-51 mm) of precipitation in June and September and 2-3 inches (51-76 mm) in July and August. Figure 7-24 depicts the mean number of days with precipitation and thunderstorms during the season across the region.

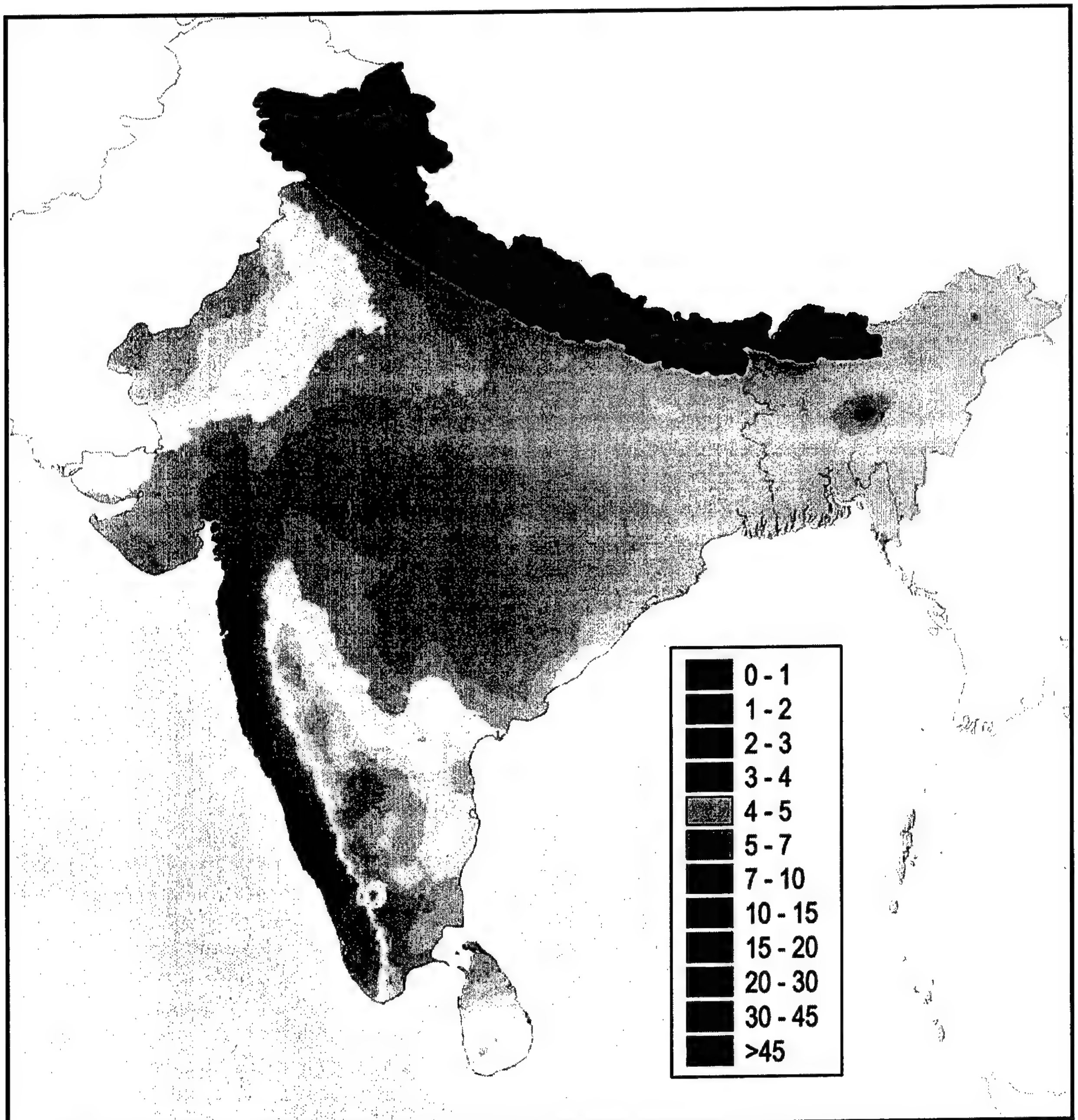


Figure 7-23. July Mean Precipitation (Inches). The isopleths depict the mean precipitation totals received during the most representative month of the southwest monsoon season.

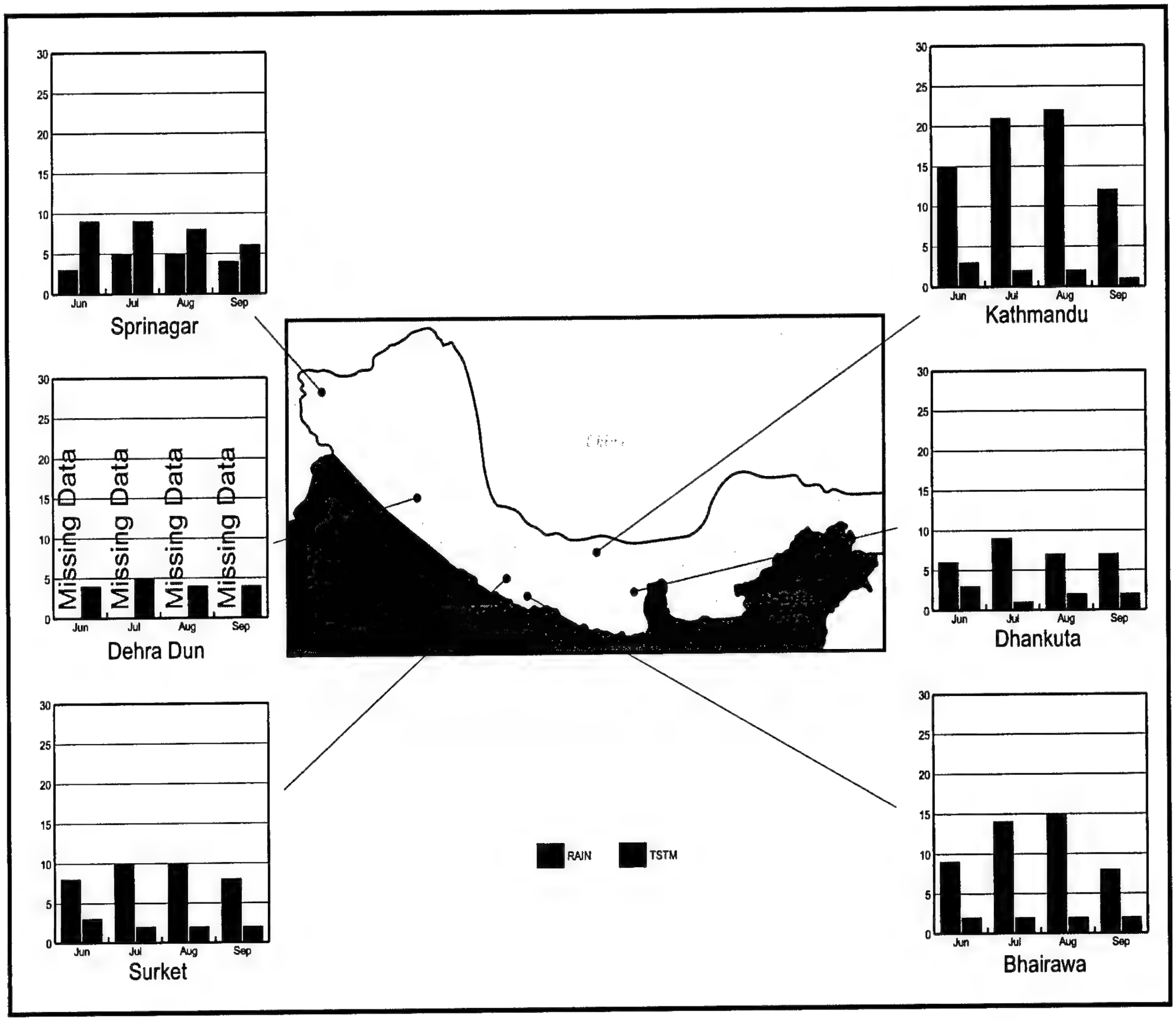


Figure 7-24. Southwest Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region.

Temperatures Temperatures across the Himalayas are moderated by a combination of elevation of the station, cloud cover, and rainfall. Since this is the wettest season for most stations, the range between mean highs and lows is smaller than in other seasons. Additionally, the high incidence of low ceilings across the region restricts solar heating. Conversely, since low ceilings occur more frequently at night and in the early morning, less heat radiates away. See Figures 7-25 and 7-26.

Mean highs across the eastern half of the region usually peak in June or July. Across the western half, mean highs usually reach an annual peak in July or August. In the eastern half, mean highs range from 67°F (19°C) at Darjeeling to 80°F (27°C) at Kathmandu. Across the west, mean highs range from 73°F (23°C) at Mukteswar to 94°F (34°C) at Dehra Dun. Even though Leh and Dras are above 10,000 feet (3,000 meters) elevation, the lack of cloud cover and rainfall allow these usually cool cities to record a mean high temperature of 77°F (25°C).

The extremely heavy precipitation and high incidence of low ceilings keeps the mean low at Darjeeling fairly uniform all season. The mean low of 58°F (14°C) in July is only 9 Fahrenheit (5 Celsius) degrees lower than the mean high. Across most of the rest of the region, the difference between mean highs and lows averages 10-15 Fahrenheit (6-8 Celsius) degrees. Areas that do not receive as much precipitation or cloud cover have a much larger spread. At Srinagar, the difference is 24 Fahrenheit (13 Celsius) degrees. At arid locations, like Leh and Dras, the difference is 26-28 Fahrenheit (14-16 Celsius) degrees. In July, mean lows range from 49°F (9°C) at Dras to 74°F (23°C) at Dehra Dun. Most locations record mean lows in the 60° to 69°F (16° to 21°C) range.

Extreme highs and lows across the region are also moderated by available moisture from the southwest monsoon. Little moisture and low elevation allowed Dehra Dun to record an extreme high of 111°F (44°C). Heavy rainfall, continuous cloud cover, and high elevation kept the extreme highs at Darjeeling at 84°F (29°C). Extremely dry conditions at Leh and Dras allowed for an extreme high of 93°F (34°C). The coldest extreme lows are mainly recorded in September. A few stations have extreme lows recorded in June. The coldest September temperature was 20°F (-7°C) at Leh. A close second was 22°F (-6°C) recorded at Dras. Most stations across the Himalayas record their warmest extreme lows in August. Extreme lows range from 36°F (2°C) at Dras to 63°F (17°C) at Dehra Dun. Moisture plays the greatest role in determining ranges between the extreme highs and lows. The arid city of Dras has a range from extreme high to extreme low of 57 Fahrenheit (32 Celsius) degrees, while the moist city of Darjeeling has a range of 44 Fahrenheit (24 Celsius) degrees.

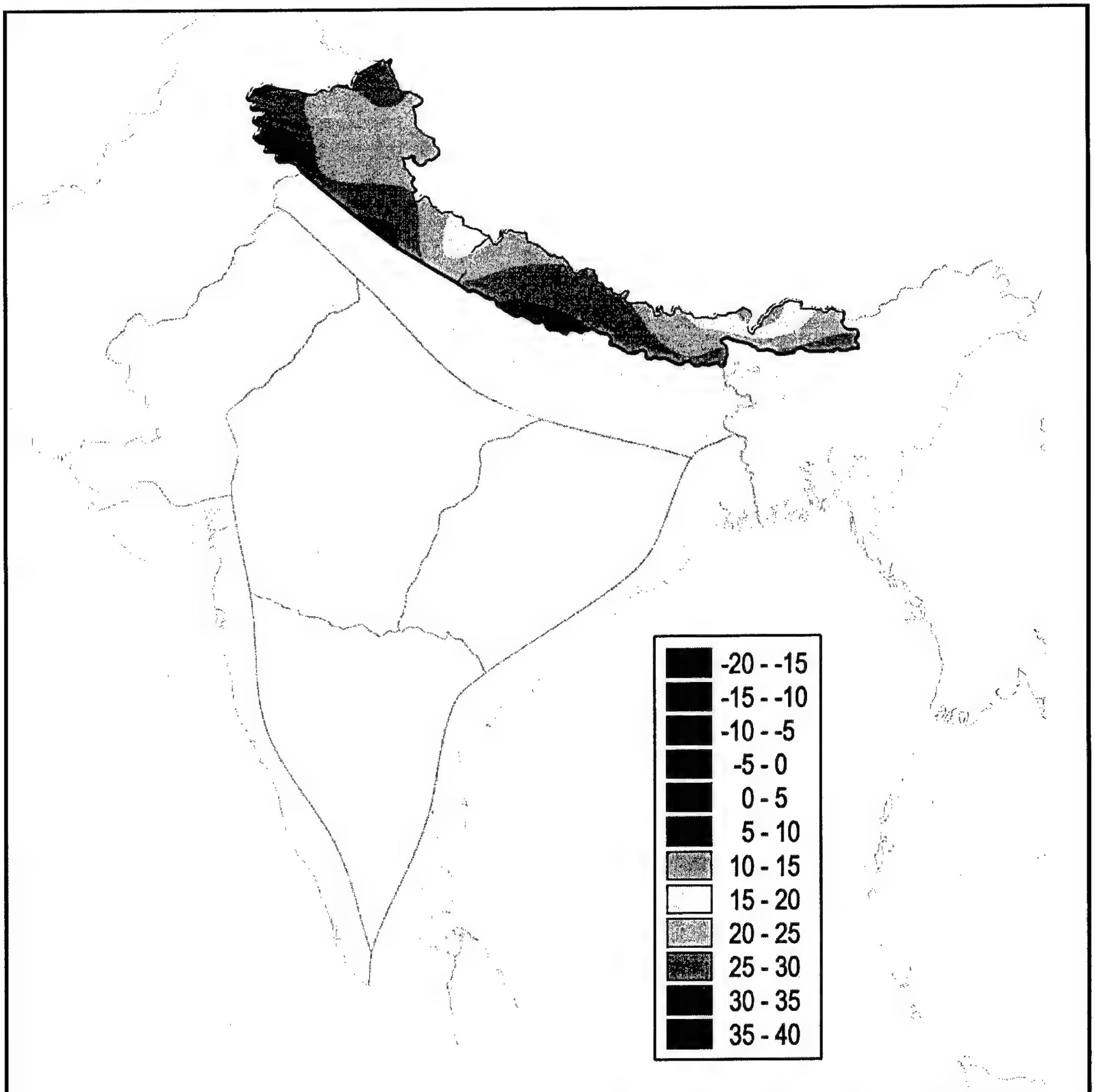


Figure 7-25. July Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures for July. Daily high temperatures are often higher than the mean. Mean maximum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

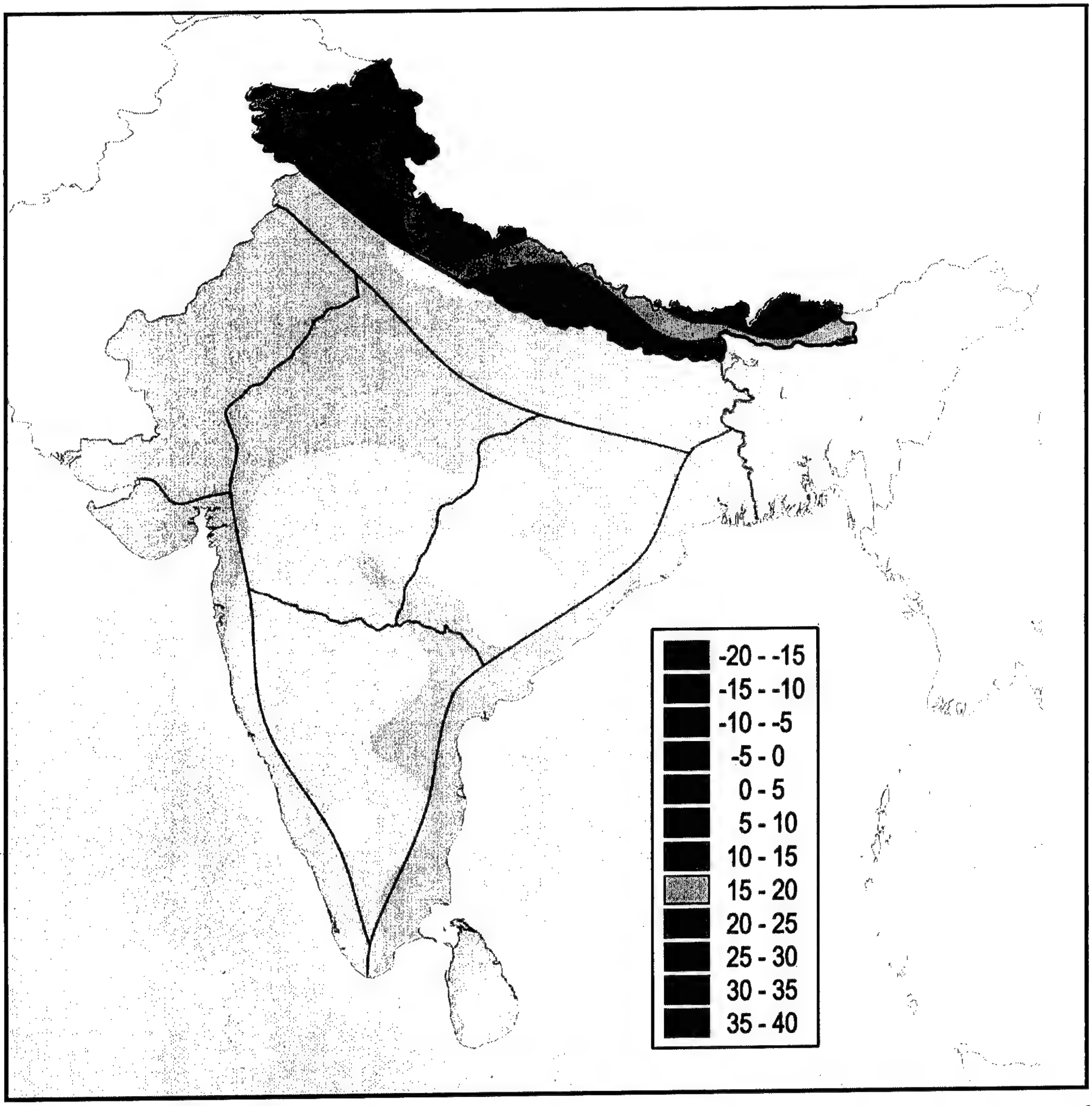


Figure 7-26. July Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures for July. Daily low temperatures are often lower than the mean. Mean minimum temperatures during other southwest monsoon months may be higher or lower, especially at the beginning and ending of the season.

Post-Monsoon

General Weather. This brief interlude between the southwest monsoon and winter is highlighted by a transition from easterlies to westerlies. As the season begins, the subtropical ridge is south of the region and the STJ moves into Kashmir. Weak, easterly flow remains over the eastern third of the region, but is eliminated as the Tibetan upper-level anticyclone and the Asiatic low disappear. The moist, unstable, cyclonic flow across Asia is replaced by dry, stable, anticyclonic flow associated with the Asiatic high. By late November, the Asiatic high is firmly entrenched; this marks the beginning of winter.

The southwest monsoon quickly withdraws from the area by early October. After the Asiatic high develops, northeast outflow from the high creates a lee-side trough south of the Himalayas. The trough develops by late October and is firmly in place by mid-November. The lee-side trough reinforces western disturbances that pass through the region. The first early disturbances arrive in Kashmir by mid October and bring the first snow of the season to the northwestern Himalayas. The main core of the STJ moves south of the Himalayas by late October and overlays the lee-side trough. Most of the precipitation falls over Kashmir, and precipitation amounts gradually decrease as the systems continue eastward.

Sky Cover. The post- monsoon season generally brings improved conditions to the Himalayas. The moist, tropical air of the southwest monsoon is replaced by dry, continental air of the Asiatic high. Locations that had low ceilings because of the easterly flow during the southwest monsoon improve greatly. Conversely, the migratory systems that come in on the prevailing westerlies brings a greater incidence of low ceilings to Srinagar. This city, on the eastern edge of the Vale of Kashmir in the western foothills of the Himalayas, sees a slight increase in the amount of ceilings below 5,000 feet. In October, Srinagar records ceilings below 5,000 feet 19-26 percent of the time. The October preponderance of late evening low ceilings changes to early morning in November. Srinagar records ceilings below 5,000 feet 22-36 percent of the time in November.

Across most of the rest of Kashmir, Uttar and Himachal Pradesh, and western Nepal, ceilings below 5,000 feet occur less than 10 percent of the time. Several sites in the lee of the Himalayas record them less than 5 percent of the time. The retreat of tropical moisture is notable at Dehra Dun and Mussoorie. In October, these two cities report ceilings below 5,000 feet 6-11 and 19-45 percent of the time, respectively. By November, the percentage drops to less than 3 percent of the time at Dehra Dun and 5-25 percent of the time at Mussoorie. For both months, the higher figure occurs in the late afternoon, and the low figure occurs in the early morning.

This trend continues across most of Nepal. The exception occurs at Kathmandu. The season begins with noticeable improvement, however by November, the radiation inversion at Kathmandu strengthens and is reinforced by the Asiatic high. This causes a slight increase in the incidence of low ceilings at all levels over Kathmandu. Ceilings below 3,000 feet occur 13 percent of the time in October and 14 percent of the time in November. The intensification of the inversion is also noted by the general increase in ceilings below 500 and 1,000 feet. The ratio of ceilings below 500 feet to ceilings below 3,000 feet increases from October to November. Ceilings below 500 feet occur 9 percent of the time in October, and 11 percent of the time in November. The disappearance of the easterlies brings a dramatic improvement in conditions to Darjeeling, however, this city in Sikkim still records the highest incidence of ceilings below 5,000 feet of any station in the Himalayas. Darjeeling has ceilings below 5,000 feet 47-55 percent of the time in October and 34-47 percent of the time in November. Darjeeling also has ceilings below 1,000 feet 35 percent of the time in October, and 22-31 percent of the time in November. Figure 7-27 shows occurrence rates of ceilings below 5,000 feet at representative stations within the region.

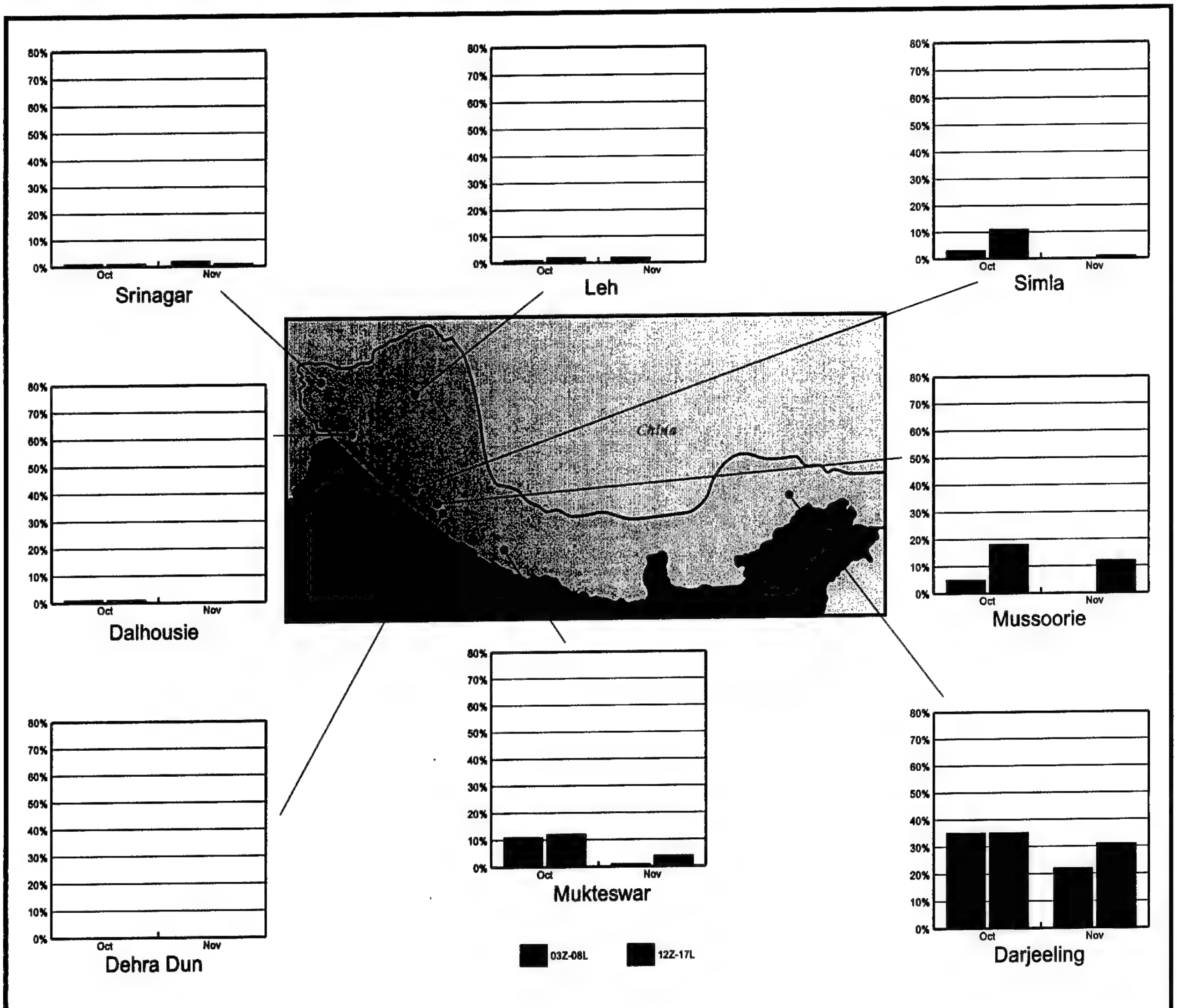


Figure 7-27. Post-Monsoon Season Percent Frequency of Ceilings below 5,000 Feet. The graphs show a monthly breakdown of the percent of ceilings below 5,000 feet based on location and diurnal influences.

Visibility. As the westerlies strengthen and bring more migratory systems through the region, visibility gradually deteriorates across western Kashmir. Fog, rain, and snow are the causes, primarily fog. Even though fog is common, it quickly burns off by late morning. Upslope conditions on the western slopes of the Himalayas trap fog in the Vale of Kashmir. Srinagar has morning visibility below 2 1/2 miles (4,000 meters) 10 percent of the time in October and 25 percent of the time in November. Afternoon visibility drops below 4,000 meters 6 percent of the time in October and 12 percent of the time in November. While visibility below 1 1/4 mile (2,000 meters) occurs less than 10 percent of the time at Srinagar, there is a fourfold increase in frequency from 2 percent of the time in October to 8 percent of the time in November. Leh and Dras, in the lee of the Himalayas, have visibility below 4,000 meters less than 8 percent of the time.

Farther east, most stations in Uttar and Himachal Pradesh experience a general improvement of conditions. The absence of southwest monsoon moisture and the influx of cool, dry air causes allows fog to occur 10 percent of the time or less. Mandi, a station on the western slopes of a Himalayan spur, gets the brunt of transient systems. Mandi has morning visibility below 4,000 meters 20 percent of the time in October and 32 percent of the time in November. The incidence of visibility below 2,000 meters also increases from 16 percent of the time in October to 27 percent of the time in November.

Across Nepal, the occurrences of visibility below 3 miles (4,800 meters) due to fog increase. Surkhet has visibility below 4,800 meters 21 percent of the time in October and 25 percent of the time in November. Bhairawa experiences a dramatic increase from 55 percent of the mornings in October to 78 percent of the mornings in November. Bhairawa, on the southern slopes of the Siwaliks, gets a great amount of upslope fog. At Bhairawa, visibility drops below 1 mile (1,600 meters) 16 percent of the time in October and 26 percent of the time in November. The return of the Asiatic high causes the inversion over Kathmandu to strengthen and trap fog and man-made pollutants. Visibility at Kathmandu drops below 4,800 meters on 64 percent of the mornings in October and 81 percent of the mornings in November. Katmandu also averages visibility below 1 1/2 mile (2,400 meters) and below 1/2 mile (800 meters) on 41 and 31 percent of the mornings in October and 51 and 39 percent of the mornings in November. The inversion quickly breaks and conditions rapidly improve by late morning. Reduced visibility occurs on less than 5 percent of the afternoons at Kathmandu.

Across eastern Nepal, Sikkim, and Bhutan conditions gradually improve during the post-monsoon. Nocturnal and morning visibility below 4,800 meters occurs at Dhankuta 16 percent of the time in October and 5 percent of the time in November. Darjeeling also experiences a slight improvement in visibility. It has visibility below 4,000 meters on 39 percent of October mornings and 61 percent of October afternoons. In November, these rates drop to 31 percent of the mornings and 54 percent of the afternoons. Additionally, visibility below 2,000 meters occurs less frequently in November than during October. Darjeeling has visibility below 2,000 meters on 31 percent of October mornings and 40 percent of the October afternoons. In November, it occurs 17 percent of the mornings and 28 percent of the afternoons. Fog commonly forms in the valley below Darjeeling, and as it lifts by late morning, moves up the valley and into Darjeeling. Conditions across Bhutan are generally excellent in the lee valleys and marginal in the south. The southern slopes of the Siwaliks are particularly prone to upslope fog in the mornings. Visibility drops in brief snow showers that affect the higher elevations of the Bhutanese Himalayas by mid October. Figure 7-28 shows the percent frequency of visibility below 4,000 meters at various locations within the region.

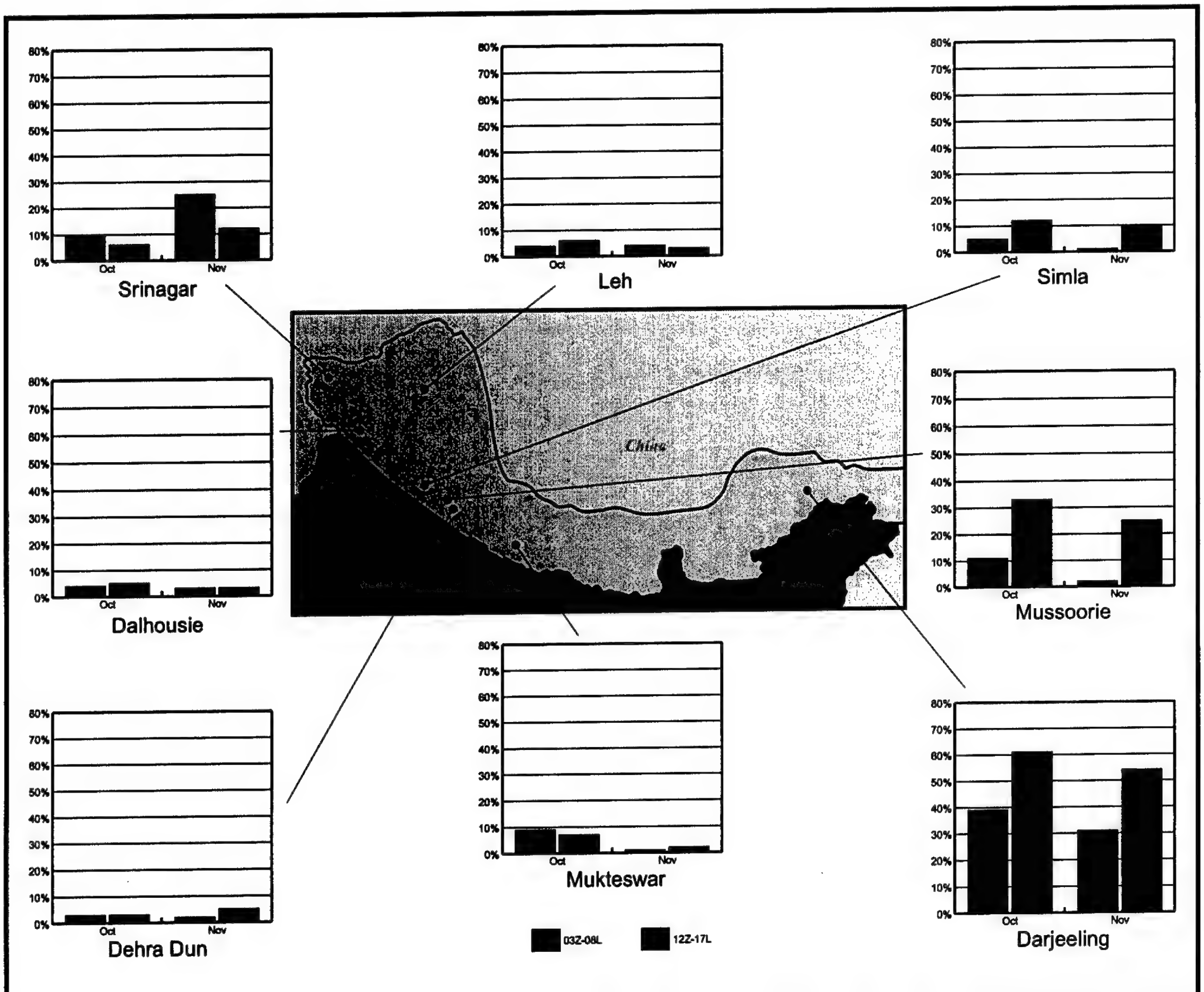


Figure 7-28. Post-Monsoon Season Percent Frequency of Visibility below 2 1/2 Miles (4,000 Meters). The graphs show a monthly breakdown of the percent of visibility below 4,000 meters based on location and diurnal influences.

Surface Winds. Where not dominated by terrain and local effects, the surface winds in this transition season reflect the large-scale shift from easterlies to westerlies. The strong nocturnal easterlies that affected Bhairawa during the southwest monsoon are replaced by calm winds during the post-monsoon. Bhairawa has nocturnal and early morning calms 90 percent of the time in October and 97 percent of the time in November. As soon as the inversion breaks by late morning, Bhairawa records a weak (0-7 knots) easterly breeze 10-20 percent of the time in both months and a weak westerly breeze 10-15 percent of the time. A shift in the winds also occurs at Kathmandu. The afternoon easterly wind, detected about 20 percent of the time in previous months, almost disappears. Kathmandu has afternoon westerly breezes about 60 percent of the time in both months. In the Vale of Kashmir, Srinagar has mostly light and variable winds. During the night, Srinagar records calms 80-85 percent of the time. Even during the afternoon, Srinagar has calms 60-69 percent of the time. Winds at Srinagar rarely exceed 8 knots, even from the most favored wind direction, northwesterly. A slight breeze blows through the Vale along the Jhelum River. See Figure 7-29 for surface wind roses at representative regional locations.

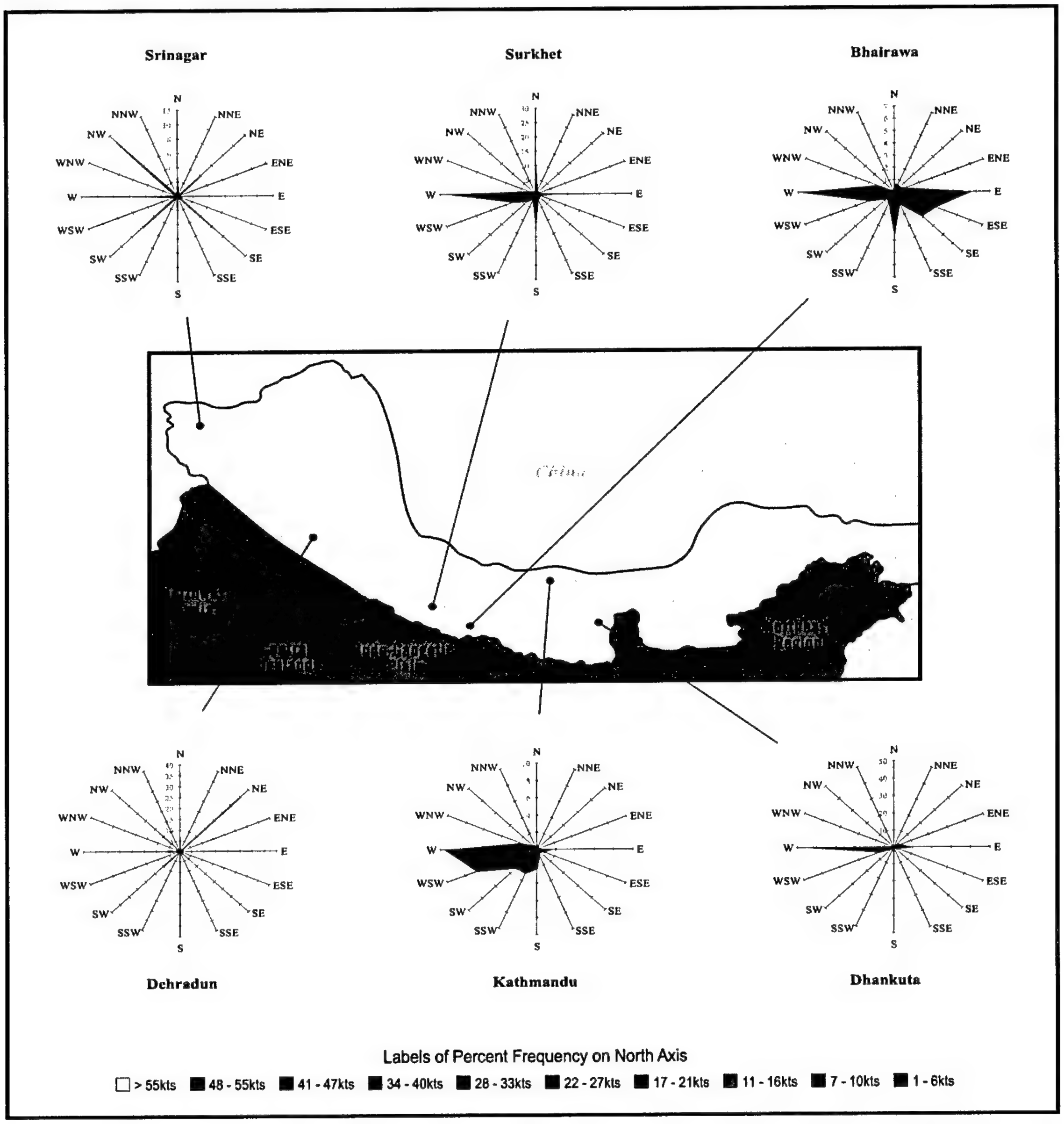


Figure 7-29. October Surface Wind Roses. The figure shows the prevailing wind direction and range of speeds based on frequency and location.

Upper-Level Winds. By October, the main core of the STJ moves south over northern Kashmir. The main jet is a 50-knot band of winds best represented at 200 mb. Speeds above 90 knots occur 5-10 percent of the time. Wind speeds gradually increase as the jet continues south. By November, the main jet core is a 50-75 knot band of winds that extends from southern Kashmir to just north of Nepal and Bhutan. The segment of the jet from north of Nepal to Bhutan is somewhat stronger, mainly 75-100 knots. By the end of November, the STJ extends from southern Kashmir to southern Nepal and Bhutan. Depending on the elevation of a location, both friction and other terrain effects influence the wind speed and direction for nearly every upper-level pressure surface from 850 mb to 400 mb. Figure 7-30 shows typical upper-level for winds over at Srinagar, India.

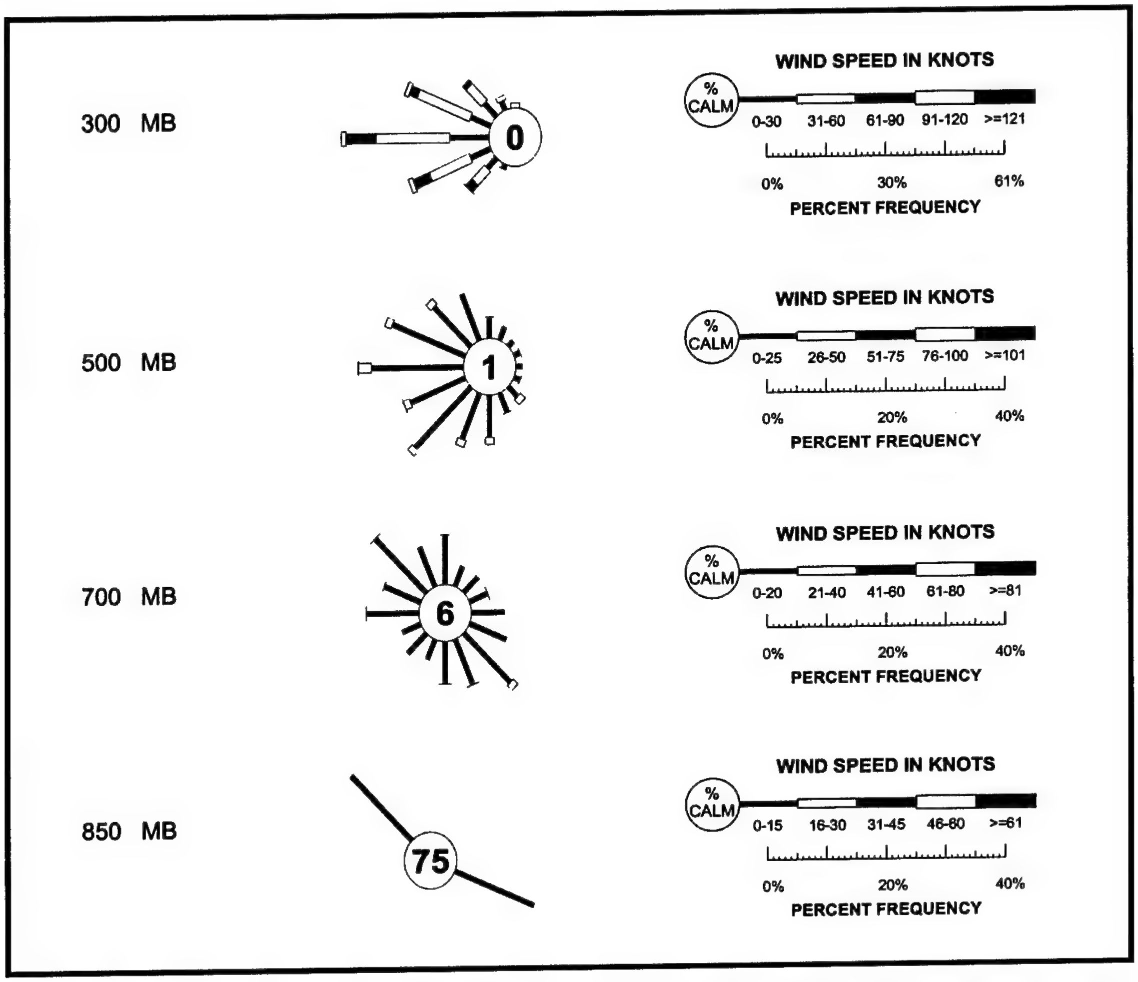


Figure 7-30. October Upper-Air Wind Roses. The wind roses depict wind speed and direction for standard pressure surfaces between 850 mb and 300 mb over Srinagar, India.

Precipitation. For many locations, the post-monsoon season is the driest season of the year. In October, moist easterlies linger over the eastern third of the region and westerlies are gaining strength in the far west. The highest precipitation totals are in southern Sikkim and Bhutan, but precipitation there quickly decreases in November. Overall, November is the driest month of the year. Migratory systems move through more frequently, but they are weak and do not have a great deal of moisture with them. Most of the precipitation with migratory systems falls in a narrow swath of the western Himalayas southeast of the Vale of Kashmir. As these systems move east, little precipitation falls on the rest of the region. By the end of the season, the entire region comes under the influence of the migratory systems associated with the STJ.

Southern Bhutan and Sikkim record the highest precipitation amounts during October (see Figure 7-31). Most of the southern half of this area gets 4-6 inches (102-152 mm). The southern slopes of the central Siwaliks have over 8 inches (203 mm) in October. While the southern half of the area records high precipitation amounts from the retreating easterlies, the northern portions of Sikkim and Bhutan are dry. The area in the lee of the Himalayas near the Chinese border, records less than one inch (25 mm) in October. In November, precipitation amounts across Sikkim and Bhutan decrease dramatically under dry, northeasterly outflow from the Asiatic high. Southern Sikkim and Bhutan record about one inch (25 mm) of rainfall in November; most of this probably due to the remnants of the easterlies in early November. Because of the extremely dry air associated with the Asiatic high, north of the Himalayas, precipitation is nearly nonexistent. Near the Chinese border, less than 0.2 inch (5 mm) is recorded in November.

To the west, in October, eastern Nepal averages 2-4 inches (51-102 mm) of precipitation. Like Bhutan and Sikkim in November, most of the October precipitation across eastern Nepal is from the last vestiges of the waning easterlies. By November, even this meager rainfall disappears. Most of eastern Nepal records less than one inch (25 mm) of precipitation in November. North of the Himalayas, near the Chinese border, precipitation totals drop from one inch (25 mm) in October to less than 0.2 inch (5 mm) in November. Farther west, precipitation totals decrease from October to November. However, the drop is not nearly as drastic as across the eastern half of the Himalayas.

While the eastern Himalayas are losing their primary precipitation driver (the easterlies), decreases in precipitation across the western half are moderated by strengthening westerlies. Western Nepal, and Uttar and Himachal Pradesh average 1-2 inches (25-51 mm) in October and one inch (25 mm) in November. Although the precipitation gradient in the eastern half of the region is oriented north-south, it is oriented west-east in the western half. The gradient occurs in the rain shadow of the Himalayas and is particularly evident in the main river valleys from west-central Nepal to southern Kashmir.

In Kashmir, the heaviest precipitation is concentrated in a small area just southeast of Srinagar. In October, this area receives up to 6 inches (152 mm) of precipitation. The rest of the western Himalayas receive 2-3 inches (51-76 mm), mostly in light, but steady snow. In November, the west-central Himalayas receives more than 2 inches (51 mm), the most in the entire region.

Figure 7-32 shows the mean number of precipitation and thunderstorm days in the Himalayas during the season.

The Pir Panjal Mountains to the west of the Vale average 1-2 inches (25-51 mm) in October and slightly more than one inch (25 mm) in November. The Indus River valley and the Ladakh Mountains get very little precipitation in the Himalayan rain shadow. In October, the Ladakh Mountains receives 0.4-1 inch (10-25 mm) of precipitation. This amount decreases to barely a trace in November. In the direct rain shadow of the Himalayas, the Indus River valley is the driest area of the entire region. The Indus River valley receives barely more than a trace of precipitation in both October and November. In the rain shadow of the smaller Pir Panjal, and on the windward slopes of the Himalayas, the Valeof Kashmir and the Jhelum River valley get 1-2 inches (25-51 mm) in October, and slightly less than one inch (25 mm) in November.

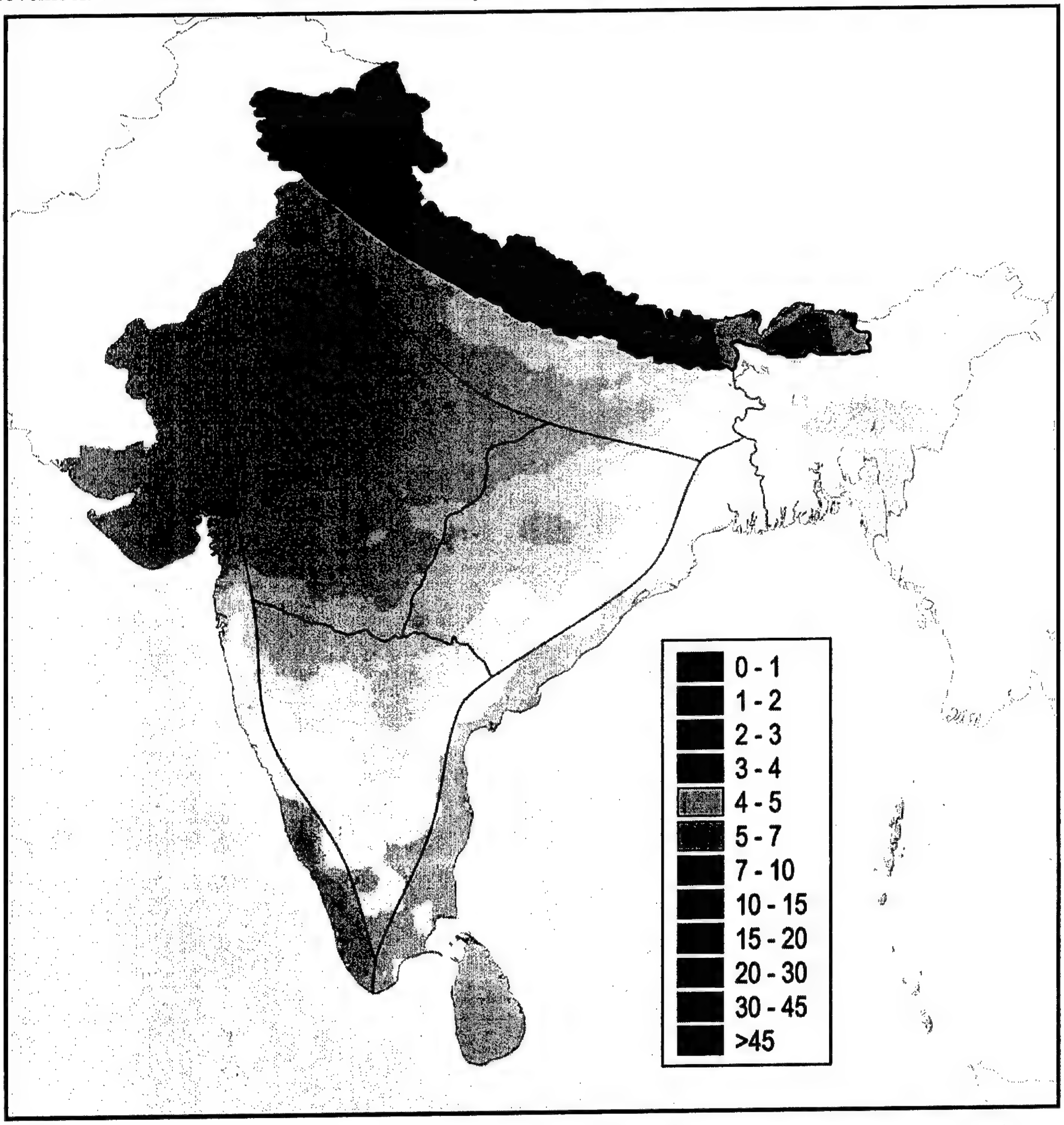


Figure 7-31. October Mean Precipitation (Inches). The figure depicts the mean precipitation totals received during October, the most representative month of the post-monsoon season.

Thunderstorms rarely occur in October, and then only in the Siwaliks, probably orographically-induced. By November, they typically do not occur anywhere in the region. Precipitation falls only around 2-3 days a month in October and decreases to only 1-2 days in November. Towards the Chinese border, days with precipitation are rare in November. See Figures 7-28 and 7-29 for October mean precipitation amounts and seasonal thunderstorm and rain days, respectively.

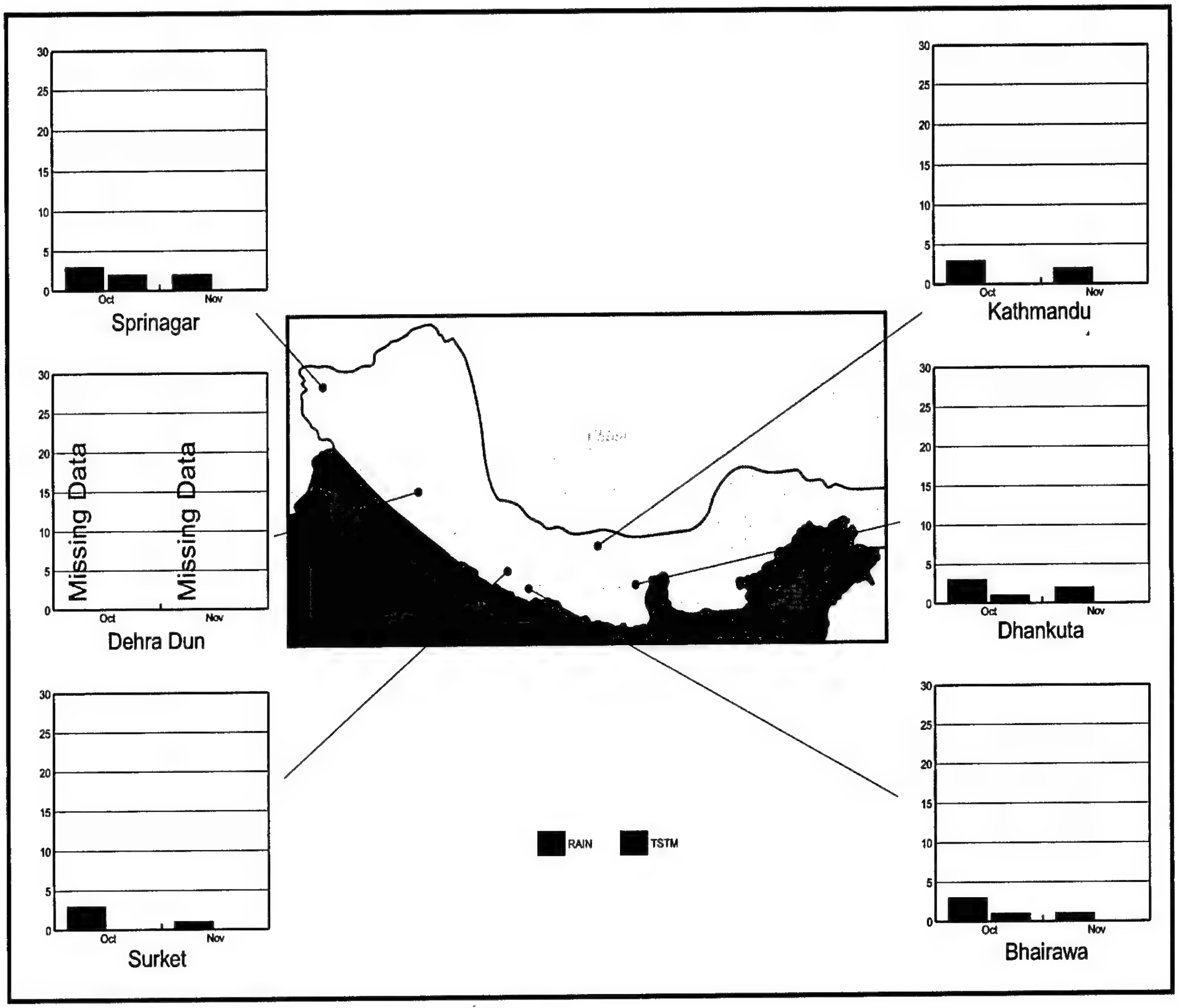


Figure 7-32. Post-Monsoon Mean Precipitation and Thunderstorm Days. The graphs show the average seasonal occurrences of rain and thunderstorm days for representative locations in the region. Note: The rain in the legend also includes the water equivalent of snowfall.

Temperatures. Temperatures are largely a function of moisture. As the easterlies retreat, drier air brings a greater diurnal temperature range. Although the mean highs drop because of less solar radiation, the mean lows drop even quicker. The drop in temperatures is most noticeable at higher elevations. Also, at the beginning of the season, the change in temperatures from the end of the southwest monsoon to the post-monsoon season are less extreme in the east because of the lingering moisture. Mean highs at the beginning of the season drop by an average of 10-12 Fahrenheit (6-7 Celsius) degrees for the highest elevations of Kashmir and about 2-3 Fahrenheit (1-2 Celsius) degrees across eastern Nepal, Sikkim, and Bhutan.

The warmest mean highs for October and November are at Dehra Dun. This station has the lowest elevation of any station in the region. The mean high is 83°F (28°C) in October and 75°F (24°C) in November. Mean highs are also warm at Kathmandu, 80°F (27°C) in October and 75°F (24°C) in November. The coolest mean highs are in Kashmir, at Leh and Dras. The mean high in Dras is 56°F (13°C) for October and 40°F (4°C) for November. Leh is nearly as cool, with an October mean high of 59°F (15°C) and a November high of 47°F (8°C). Most of the rest of the region records October highs of 64°-70°F (18°-21°C). November highs across most of the region are 56°-64°F (13°-18°C).

Mean lows drop off quickest at higher elevations, and mostly across the west. At the beginning of the season, the mean low at Dras drops to 29°F (-2°C) in October and to 14°F (-10°C) in November. These are also the coolest mean lows of any location in the region. East of Kashmir, most of the rest of the region records a drop of about 2-6 Fahrenheit (1-3 Celsius) degrees in the mean lows at the beginning of the season. By November, the air mass across most of the region is dry and more susceptible to greater variations in temperature. The drop of 15 Fahrenheit (8 Celsius) degrees from October to November at Dras, is the largest month-to-month change in the region. The rest of the region has a October-November change from 6 Fahrenheit (3 Celsius) degrees at Mussoorie to 10 Fahrenheit (6 Celsius) degrees at Kathmandu and Simla. The warmest mean lows are at Dehra Dun. In October, this city averages a mean low of 60°F (16°C). By November, the mean low of 51°F (11°C) is still the warmest in the region. Figures 7-33 and 7-34 show the respective mean maximum and minimum temperatures for October across the region.

Extreme highs for October range from 77°F (25°C) at Dras and other numerous locations, to 97°F (36°C) at Dehra Dun. Most of the rest of the region recorded extreme highs of 81°-93°F (27°-34°C). In November, the extreme highs range from 59°F (15°C) at Dras to 88°F (31°C) at Dehra Dun. Extreme highs for November across most of the rest of the region are 71°-85°F (22°-29°C). Extreme lows are highly dependent upon atmospheric moisture. In October, only stations in Kashmir have extreme lows below freezing. By November, after the last residual monsoonal moisture has left the rest of the region, nearly every other station recorded an extreme low below freezing. Extreme lows for October range from -4°F (-20°C) at Dras to 48°F (9°C) at Dehra Dun. In November, the extreme lows drop from -21°F (-29°C) at Dras to 37°F (3°C) at Dehra Dun.

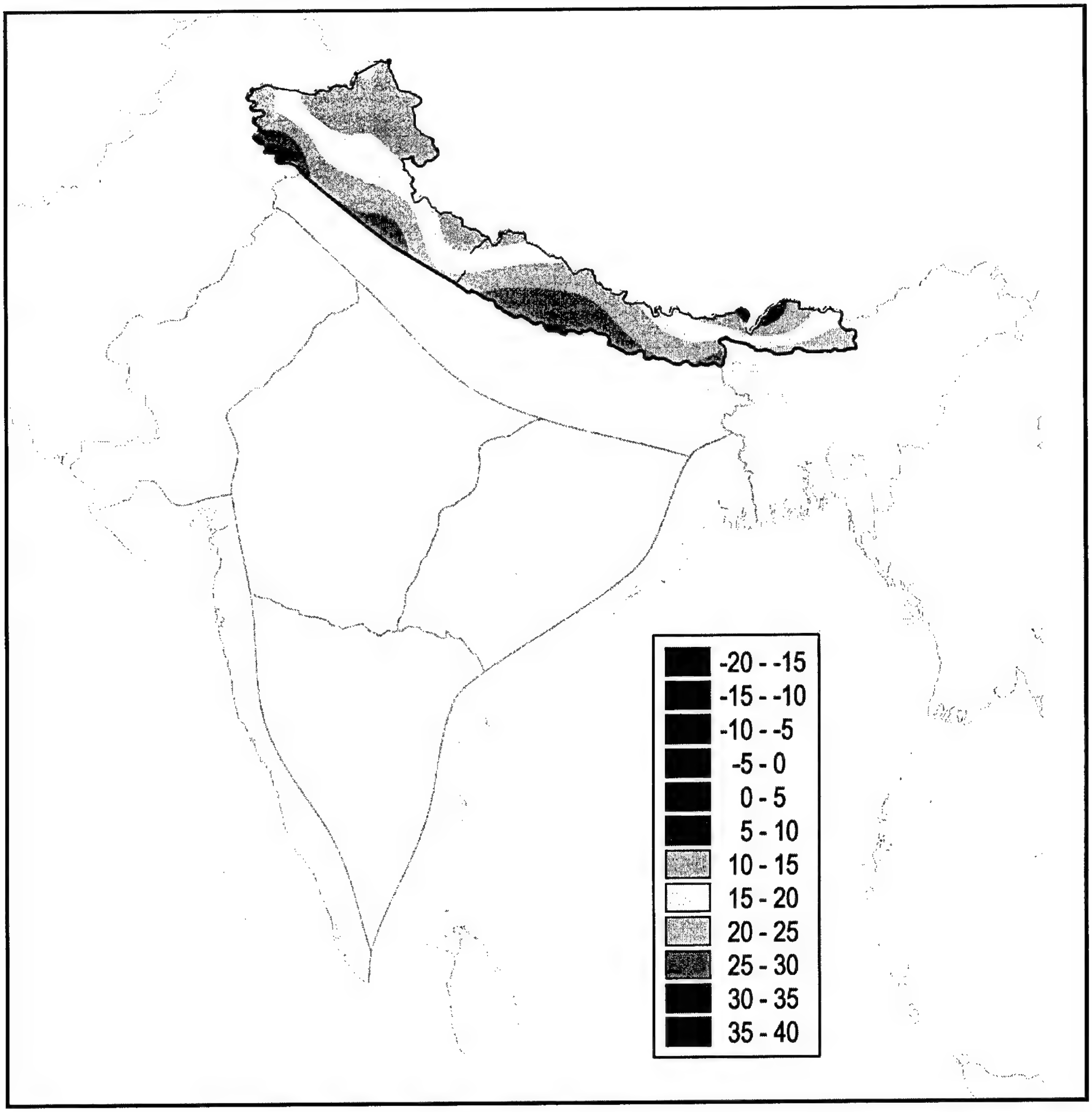


Figure 7-33. October Mean Maximum Temperatures (°C). Mean maximum temperatures represent the average of all high temperatures in October. Daily high temperatures are often higher than the mean. Mean maximum temperatures during November may be lower.

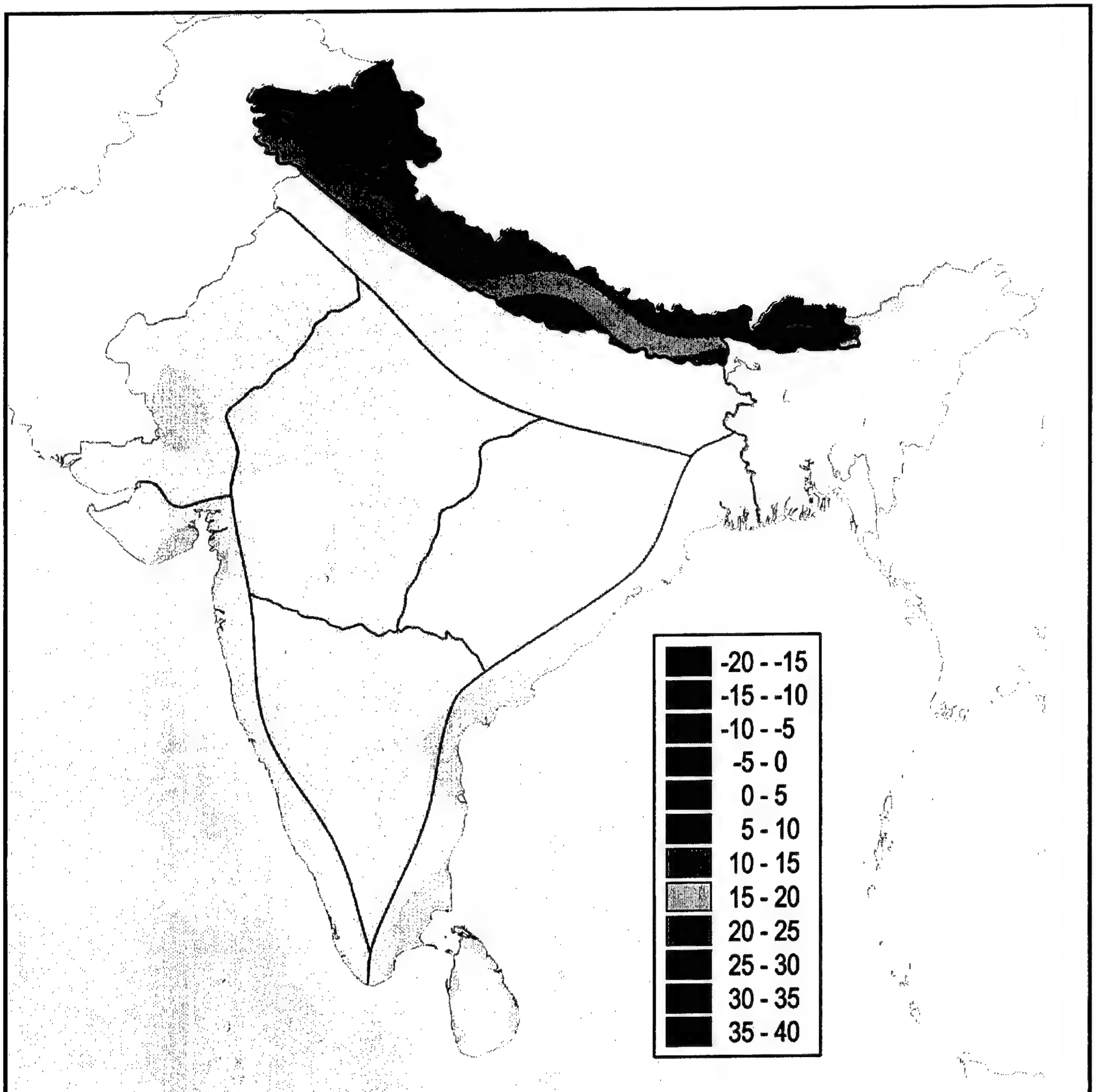


Figure 7-34. October Mean Minimum Temperatures (°C). Mean minimum temperatures represent the average of all low temperatures in October. Daily low temperatures are often lower than the mean. Mean minimum temperatures during November may be lower.

BIBLIOGRAPHY

Alford, D., *Notes on High Elevation Research with Selected Bibliography*, Defense Technical Information Center, Fort Belvoir, VA, August 1965

Ahmed, F., et al, "A Climatological Sturdy of Absolute Minimum Temperatures in Bangladesh," *Chittagong University Studies, Part II (Science)*, Vol. 8, No. 1, pp 107-114, 1984

Ahmed, R, "Duration and Rainfall Characteristics of the Summer Monsoon in Bangladesh," 90th Annual Meeting, Association of American Geographers, San Francisco, 29 Mar - 2 Apr 1994

Alford, D., *Notes on High Elevation Research with Selected Bibliography*, Defense Technical Information Center, Fort Belvoir, VA, August 1965

Ananthakrishan, R., "Some Aspects of the Monsoon Circulation and Monsoon Rainfall," *Pure and Applied Geophysics*, Vol. 115, No. 5-6, pp 1209-1249, 1977

Ananthasayanam, M. and Narashima, R., "Standards for the Tropical Indian Atmosphere," *Space Research, Vol. 20 - Proceedings of the Open Meetings of the Working Groups on Physical Sciences*, pp 25-58, 29 May -9 Jun 1979

Arkin, P., et al, "Indian Monsoon Rainfall, 1986-1987," National Weather Service, *Proceedings of the Twelfth Annual Climate Diagnostics Workshop*, pp 14-23, Mar 1988

Asnani, G., *Tropical Meteorology, Volume 1*, Noble Printers, Pune, India, 1993

Atkinson, G., and Sadler, J., *Mean-Cloudiness And Gradient-Level Wind Charts Over The Tropics*, AWS TR 215 Vols. I and II, Air Weather Service, Scott AFB, IL, 1970

Awasthi, A., *Indian Climatology*, APH Publishing Corporation, New Delhi, 1995

Banerji, R. and Upadhyay, D., "A Survey of Drought and Scarcity in Rajasthan," *Proceedings of the Indian Academy of Science,* Part A, Vol. 42, No. 1, pp 15-21, 1976

Cadet, D., "Meteorology of the Indian Summer Monsoon," *Nature*, Vol. 279, No. 5716, pp 761-767, 1979

Central Intelligence Agency, *Burma, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1967

———, *India and Pakistan, Section 23: Weather And Climate*, Defense Technical Information Center, Fort Belvoir, VA, 1966

Cheang, B., "Short- And Long-Range Monsoon Prediction In Southeast Asia," *Monsoons,* pp. 579-606, John Wiley & Sons, Inc., New York, 1987

——— and Tan, H., "Some Aspects of the Summer Monsoon in South-East Asia May to September 1986," *Australian Meteorological Magazine*, Vol. 36, No. 4, pp. 227-233, 1988

Chen, R., "Characteristics of the Air Current and Sub-Synoptic Scale Events Within a Summer Monsoon Cyclone Over the Arabian Sea," *Scientia Atmospherica Sinica*, Vol. 5, No. 3, pp 366-368, 1981

Chin, P. and Lai, M., "Monthly Mean Upper Winds And Temperatures Over Southeast Asia And The Western North Pacific," *Royal Observatory Technical Memoir No. 12*, Hong Kong, 1974

Choubey, D. et al, "Terrain Classification and Land Hazard Mapping in Kalsi-Chakrata Area (Garwahl Himalaya), India," *ITC Journal*, No. 1, pp 58-66, 1990

Das, P., "Meteorology in India," *Current Science*, Vol. 50, No. 11, pp 473-479, 1981

Data, M. and Mukherjee, S., "Thunderstorm Activities in West Bengal 1968-1970," *Institution of Electronic and Radio Engineers Proceedings (India)*, Vol. 10, No. 4, pp 112-121, 1972

De, U., "Importance of Mountain Waves in Aviation and Weather Hazards Associated With It," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 60, No. 1, pp 217-226, 1994

Desai, B., "Conditions Associated with and Probable Causes of the Drought of 1899 and Other Droughts over the Indian Subcontinent During the Summer Monsoon," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 2-3, pp 149-155, 1976

Dey, S., et al, "Flood Problems in North Bengal," *Indian Journal of Power and River Valley Development*, Vol. 41, No. 10, pp 193-206, 1991

Dhar, O., et al, "Rainfall Distribution Over Indian Subdivisions During the Wettest and the Driest Monsoons of the Period 1901-1960," *Hydrological Sciences Bulletin des Hydrologiques*, Vol. 23, No. 2, pp 213-221, 1978

Ding, Y., "A Case Study of the Formation and Structure of a Monsoon Depression Over the Arabian Sea," *Scientifica Atmospherica Sinica*, Vol. 5, No. 3, pp 267-280, 1981

"Frequency Tables of Daily Rainfall - India," *Memoirs of the India Meteorological Department*, Vol. 32, Part 2, pp 29-375, 1979

Fushimi, H., et al, "Nepal Case Study: Catastrophic Floods," *International Association of Hydrological Sciences (IAHS) Publication*, Vol. 149, pp 125-130, 1985

Gadgil, S., "Orographic effects on the Southwest Monsoon: A Review," *Pure and Applied Geophysics*, Vol. 115, No. 5-6, pp 1413-1430, 1977

Glickman, T., *Glossary of Meteorology*, American Meteorological Society, Boston, 2000

Gopinathan, C., "Surface Temperature of the Equatorial Pacific Ocean and the Indian Rainfall," *Current Science*, Vol. 57, No. 21, pp 1163-1165, 1988

Goswani, B., "A Mechanism for the West-North-West Movement of Monsoon Depressions," *Nature*, Vol 326, No. 6111, pp 376-378, 1987

Hamilton, M., "Monsoons - An Introduction," *Weather*, Vol. 42, pp 186-193, 1987

Hastenrath, S., *Climate Dynamics of the Tropics*, Kluwer Academic Publishers, Dordrecht, Netherlands, 1991

Higdon, M., et al, *East Asia: A Climatological Study, Vol. II, Maritime,* AFCCC/TN-97/003, Air Force Combat Climatology Center, Scott AFB, IL, 1997

Higuchi, K., et al, "Characteristics of Precipitation During the Monsoon Season in High-Mountain Areas of the Nepal Himalaya," *International Association of Hydrological Sciences (IAHS) Publication*, Vol. 138, pp 21-30, 1982

Indian Journal of Meteorology, Hydrology, and Geophysics, Vol 28, No. 28, pp 251-252, 1977

Joint U.S. Navy/U.S. Air Force Climatic Study of the Upper Atmosphere, NAVAIR 50-1C-1/ AWS/TR-89/001, Vol. 1, January, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-4/ AWS/TR-89/004, Vol. 7, April, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-7/ AWS/TR-89/007, Vol. 7, July, Naval Oceanography Command Detachment, Asheville, NC, 1989

———, NAVAIR 50-1C-10/ AWS/TR-89/010, Vol. 10, October, Naval Oceanography Command Detachment, Asheville, NC, 1989

Kalita, S., and Sarmah, S., "Diurnal Variation of Monsoon Rainfall at an Island Station in the Brahmaputra Valley," *Current Science*, Vol. 51, No. 18, pp 881-883, 1982

——— and Sarmah, S., "On the Occurrences of Dry and Wet Sequences in the Brahmaputra Valley," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 93, No. 1, pp 27-36, 1984

Kamal, S., et al, "Some Characteristics of Rainfall in Bangladesh," *Chittagong University Studies,* Part II, Vol. 8, No. 2, pp 9-17, 1984

Kane, R., "Relationship Between the Southern Oscillation/El Niño and Rainfall in Some Tropical and Midlatitude Regions," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 98, No. 3, pp 223-235, 1989

Kattelmann, R., "Hydrologic Regime of the Sapt Kosi Basin, Nepal," *International Association of Hydrological Sciences (IAHS) Publication*, No. 201, pp 139-147, 1991

Khandeker, M. and Neralla, V., "On the Relationship Between the Sea Surface Temperatures in the Equatorial Pacific and the Indian Monsoon Rainfall," *Geophysical Research Letters*, Vol. 11, No. 11, pp 1137-1140, 1984

Koteswaram, P., "Climatological Studies of Droughts in the Asiatic Monsoon Area, Particularly India," *Proceedings of the Indian Natural Science,* Part A, Vol. 42, No. 1, pp 1-14, 1976

Laing, A. and Fritsch, J., "Mesoscale Convective Complexes over the Indian Monsoon Region," *Journal of Climate*, Vol 5, pp 911-919, May 1993

McGregor, G. and Nieuwolt, S., *Tropical Climatology - An Introduction to the Climates of the Low Latitudes*, 2nd Ed., John Wiley & Sons, Chichester, UK, 1998

Meehl, G., "Coupled Land-Ocean-Atmosphere Processes and South Asian Monsoon Variability," *Science*, Vol. 266, No. 51883, pp 263-267, 1994

Meteorological Research Committee Air Ministry, *The Upper Air Circulation in Low Latitudes and Its Relation to Certain Climatological Discontinuities*, Defense Technical Information Center, Fort Belvoir, VA, January 1952

Mishra, D. and Jain, R., "Characteristics of Cloud Features Associated with Monsoon Depressions Observed in Satellite Imagery," *Indian Journal of Radio and Space Physics*, Vol. 8, pp 201-206, 1979

Mohana Roa, N., "Rainfall Fluctuations - Break-Associated Synoptic Systems," *Pure and Applied Geophysics*, Vol. 109, No. 8, pp 1877-1891, 1973

Mohanty, U. and Das, S., "On the Structure of the Atmosphere During Suppressed and Active Periods of Convection over the Bay of Bengal," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 52, No. 3, pp 625-640, 1986

Mooley, D. et al, "Relationship Between the All-India Summer Monsoon Rainfall and Southern Oscillation/Eastern Equatorial Pacific Sea Surface Temperature," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 94, No. 2, pp 199-210, 1985

——— and Parthasaranthy, B., "Indian Summer Monsoon and El Niño," *Pure and Applied Geophysics*, Vol. 121, No. 2, pp 339-352, 1983

——— and Munot, A., "Variations in the Relationship of the Indian Summer Monsoon with Global Factors," *Proceedings of the Indian Academy of Sciences, Earth and Planetary Sciences*, Vol. 102, No. 1, pp 89-104, 1993

Moray, P., "Periodicity of Drought Occurrence in India," *Proceedings of the Indian Natural Science Academy,* Part A, Vol. 42, No. 5, pp 407-416, 1976

Muraleedharan, P. and Prasanna Kumar, D., "Equatorial Jet - A Case Study," *Indian Journal of Marine Sciences*, Vol. 21, No. 1, pp 35-45, 1992

Nieuwolt, S., *Tropical Meteorology - An Introduction to the Climates of the Low Latitudes*, John Wiley & Sons, Chichester, UK, 1977

O'Brien, J. and Hurlburt, H., *Equatorial Jet in the Indian Ocean: Theory,* Defense Technical Information Center, Fort Belvoir, VA, March 1974

Pant, G. and Rupa Kumar, K., *Climates of South Asia*, John Wiley & Sons, Chichester, UK 1997

Rajeevan, M., "Upper Tropospheric Circulation and Thermal Anomalies Over Central Asia Associated with Major Droughts and Floods in India," *Current Science*, Vol. 64, No. 4, pp 244-247, 1993